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Assessment of Muscle Fatigue in Work Related Musculoskeletal disorders by High-Density Surface Electromyography

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ABSTRACT

Work related muscle fatigue is often seen as a symptom related to musculoskeletal disorders (MSDs). These disorders had become one of the most global prevalent professional-related diseases recently, particularly in Europe. Although, The European Union has been implementing different measures through various legislations and standards, attempting to prevent or reduce this problem. However, this problem is still prevalently reported in different occupations.

This research started with a literature review on this topic. A number of relevant evidences of multi-channel surface electromyography or so-called high-density surface electromyography (HD-sEMG) applied in muscle fatigue assessment had been revealed. There were many significant findings of the feasibility and reliability of HD-sEMG in evaluation of muscle fatigue. However, none of the HD-sEMG application utilized in an industrial working condition had been found. Beside, some also suggested its capability of an initial clinical-related diagnosis utilization. Accordingly, the objectives of this thesis are: 1) to evaluate the development of muscle fatigue during the workday and workweek, 2) to identify/distinguish workers who are at risk of work-related MSDs, 3) to determine the relationship between the objective and subjective parameters, and 4) to verify the possibility of applying this type of HD-sEMG in such a real-world working condition.

The investigation was conducted in one selected food industry, operating with heavily manual handling and repetitive movement. The HD-sEMG was attached on each participating worker right-side upper trapezius. By determining through the historic medical record, diagnosed from symptom, medical examination and scan (echography) method, all 20 subjects were grouped by consisting of 13 healthy, 5 with shoulder MSDs and 2 with elbow & wrist MSDs. The surface EMG signal acquisition was conducted 5 min/session, 4 times a day: at the beginning, before the mid-day break, after resuming from the break and at the end of the workday, moreover, it was also conducted throughout the workweek.

The results revealed that: 1) EMG manifestation (RMS, MDF) clearly demonstrated the muscle fatigue development over the workday and more noticeably between the workweek. 2) The EMG manifestation also revealed the capability of pre-identifying/distinguishing workers suffering with different muscle-health conditions. 3) Considering the psychological aspect, there was likely a lower development of fatigue perception after 30 minutes lunch break. However, it was not corresponding to the one in the physical parameters. 4) The HD-sEMG had seemingly proved its performance pretty well, via its results, in muscle fatigue evaluation over the real-world working environment.

In conclusion, this research had revealed potential properties of HD-sEMG, which is well capable of applying in such industrial manual handling condition. Not only the capability of fatigue development assessment, which could be utilized in production and health-related management, but also the remarkable capability of a pre-identification of muscle-health condition being focused.

Keywords: Muscle fatigue, Work related muscle fatigue, Work-related MSDs, Surface Electromyography, High-density Surface Electromyography

RESUMO

As Lesões Músculo-Esqueléticas (LME) são uma das doenças profissionais com maior prevalência a nível mundial. Na União Europeia, tem sido considerada como a mais prevalente. Uma das causas apontadas para esta doença é a fadiga muscular provocada pelo trabalho. Na Europa têm sido implementadas várias medidas, nomeadamente através de legislação e de normas, na tentativa de evitar ou reduzir esse problema. No entanto, apesar desse esforço, as LME relacionadas ao trabalho, continuam com grande incidência em vários setores de atividade. Nessa medida constituem uma das principais motivações por trás deste estudo.

Foi este problema motivou o tema desta tese, cujo objetivo é o de estudar uma forma de avaliar a fadiga muscular em trabalhadores durante o exercício da sua atividade, usando eletromiografia de superfície multicanal.

A revisão da literatura revelou a investigação mais relevante no domínio em estudo, nomeadamente a existência de trabalhos de investigação que evidenciam a HD-sEMG como viável e confiável para determinar as características fisiológicas de músculos durante trabalho estático e dinâmico. Essas evidências indicam que a HD-sEMG pode ser utilizada em condições reais de trabalho. Contudo, não foram encontrados estudos aplicando a HD-sEMG nessas condições, apesar do seu elevado desempenho. Também não foram encontrados estudos com a sua aplicação clínica a trabalhadores com LME comparando-os com trabalhadores saudáveis. O projeto de investigação foi desenvolvido na indústria alimentar com trabalho manual repetitivo pesado. Participaram no estudo 15 voluntários saudáveis, 5 com LME no ombro e 2 com LME no pulso e no cotovelo. Foram utilizados sensores de HD-sEMG, colocados no trapézio superior direito de cada um dos voluntários. Os dados foram recolhidos em sessões de 5 minutos, repetidas quatro vezes por dia: no início do turno, antes do intervalo para almoço, após o intervalo para almoço e, no final do dia de trabalho. Este procedimento foi repetido para cada um dos voluntários ao longo de uma semana de trabalho.

Os resultados revelaram que: 1) foi possível através do EMG (RMS, MDF), detetar a evolução da fadiga ao longo do dia e da semana; 2) A EMG também revelou capacidade de pré-identificar/distinguir, trabalhadores em diferentes condições musculosqueléticas; 3) Após a pausa de 30 minutos para almoço verificou-se uma menor perceção de fadiga, contudo, a essa melhoria no aspeto psicológico não correspondeu uma melhoria nos parâmetros físicos medidos, 4) A HD-sEMG comprovou a sua capacidade de avaliar a fadiga muscular em ambiente real de trabalho.

Em conclusão, foi revelado o elevado potencial da HD-sEMG para aplicação em contexto industrial, nomeadamente em situações de tarefas repetitivas. Mostrou-se ainda a capacidade de avaliar o desenvolvimento da fadiga muscular, tanto em contexto industrial como na área dos cuidados de saúde, por permitir uma pré-identificação da saúde muscular.

Palavras-chave: Fadiga muscular, fadiga relacionada com o trabalho, LMERT, Eletromiografia de superfície, Eletromiografia de superfície de alta densidade

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LIST OF ACRONYMS

EMG: Electromyography

sEMG: Surface Electromyography

iEMG: Invasive Electromyography

HD-sEMG: High Density Surface Electromyography

MSDs: Musculoskeletal Disorders

RMS: Root Mean Square

CV: Conduction Velocity

MVC: Maximum Voluntary Contraction

PSD: Power Spectral Density

AVR: Average Rectified Value

MNF: Mean frequency of the PSD

ICC: Intra – class Correlation Coefficients

MUAP: Motor Unit Action Potential

MDF: Median Frequency

1 INTRODUCTION

Muscle fatigue involved with work-related musculoskeletal disorders (MSDs) has been reportedly documented in different occupations (Troiano et al., 2008). Musculoskeletal disorders (MSDs) are the most common work-related health problem in Europe, affecting millions of workers. Across the EU27 (European Union: 27 members), there were various kind of work related MSDs symptoms involved with such as backache, which accounts 25% of workers and along with 23% of muscular pain report (OSHA_European, 2007).

The MSDs apparently became the most major cause of work-related absence in all EU27 Member States, reducing companies' profitability and also affecting the social costs of the government. As this result, it potentially contributed to as high as 40% of workers' compensation in some EU27 states, which could cost up to about 1.6% of those countries' Gross Domestic Product (GDP) (OSHA_European, 2007).

Most of the work-related MSDs are cumulative disorders, resulting from a repeatedly exposure to high- or low-intensity loads, by over a long period of time. Its symptoms may vary ranking from a discomfort and followed by pain to a decrease of body function and invalidity (OSHA_European, 2007). The MSDs or musculoskeletal disorders are related to injuries and disorders of the soft tissues (muscles, tendons, ligaments, joints, and cartilage) and nervous system. It can potentially affect nearly all tissues, including the nerves and tendon sheaths, with the most frequently found location are on arms and the back (OSHA_U.S., 2000(Revised)). The most found-initial symptoms indicators is fatigue over those exposed muscles, involved in physical loads and consequently, pain and injury are soon developed gradually over weeks, months, and years.

Muscle fatigue is usually caused by: repetitive or sustained work, short work cycles, and localized muscle loadings. Being under muscle fatigue results in declination of force, generated by the muscle itself (Troiano et al., 2008). Muscle fatigue is developed as a result of a chain of metabolic, structural and energetic changes occurring in muscle, due to an insufficient supply of oxygen and nutritive substances carried through blood circulation, as well as a result of changes in an efficiency of the nervous system (Cifrek et al., 2009).

An intramuscular or so called invasive technique of the electromyography (EMG) signal recording was first introduced by Adrian and Bronk in 1929 (Henneberg, 2000). It is necessary to use needles inserting into the muscle being under investigation, in an attempt to accomplish the measurements of muscle EMG activity. Regarding to its properties of the diffusion effect restriction resulting from the property of the needles type electrode, it can potentially provide the well-measured potential of the active muscle fibres and this seems to clearly make this technic a classic tool for motor units properties investigation, particularly in the clinical examination (Merletti et al., 2008).

Although, the invasive technique is the perfect tool in electromyography (EMG) signal investigation, however in some cases, needles insertion is not either desirable or comfortable in utilization, for example: in children clinical examination or some activities, which require movement such as sports or ergonomics (Merletti et al., 2008).

Recently, there had been a new type of muscle examination method using ultrasound images, which is also considered as a non-invasive technique. It offers advantages over musculoskeletal disorders diagnosis and related treatment by providing pictures of muscles, tendons, ligaments, joints and soft tissue. However, by utilizing this method, it is likely still expensive and so complicated to use in such a field evaluation.

Surface EMG (sEMG) is another examination method that is a non-invasive technic as well. It is capable of utilizing as an alternative choice against such limitation, encountered by the intramuscular or invasive one, despite its poorer property, if considering in terms of clinical examination (Merletti et al., 2008). The surface EMG is utilized in measuring the mixture of muscle action potentials, conducted through surface electrodes which are placed over a muscle or group of muscles being studied (Drost et al., 2006).

A classical basic surface EMG configuration is a single channel electrode. It can provide the investigation covering just a tiny area of muscles being investigated. Furthermore, it is still incapable of investigating a spatial distribution of any muscle activity, as well as the application of an intramuscular technique (Madeleine et al., 2006a). So far, there had been a number of studies, conducted on an investigation of muscle fatigue/muscle activity by using a classic bipolar electromyography (EMG), applying over a tiny area of muscle region. Accompanying with a complexity of the surface EMG signal extraction, this may have leaded to only simple tasks were most frequently found (Farina et al., 2004b). In addition, it was evident that, isometric or constant force contraction had been selectively and preferably used in an assessment of the muscle property for over three decade (Bigland-Ritchie et al., 1981, Arendt-Nielsen et al., 1989). Consequently, as a result of its very small detected area just over the tiny portion of the muscle, this significantly leads to a rather high variance of the calculated EMG variable results, and may even be contradictory to each other (Falla et al., 2014b).

In recent years, the evolution of sEMG technology had been continuously and progressively developed over time. The new technique of two-dimensional array electrodes, so-called high-density surface electromyography (HD-sEMG) had increasingly been demonstrated and applied more widely. This technique allows the possibility of investigating muscle fatigue more comprehensively, through the larger detected skin area, with respect to the conventional bipolar one. The more dense EMG amplitude detection over larger skin, the more capability to be applied in muscle activation assessment, via motor unit distribution. In addition, it also comes with other consequent benefit, which is a reduction of the calculated EMG parameters variance (Madeleine et al., 2006a).

By conducting a systematic review, there were a number of evidences implying that: HD-sEMG is feasible and reliable in performing the application of determining physiological characteristics of muscles, whether in static or even during dynamic task. According to this information, it suggests that the HD-sEMG could also be able to apply in real-world working condition. However, it quite hard to find studies using HD-sEMG in an investigation of muscle fatigue over manual handling tasks and was carried in the real-world industrial working environment. This had prompted some existing unclear question: such HD-sEMG evaluation is actually capable of examining muscle fatigue development or even muscle condition, as well as its application as an alternative practical tool in such an industrial prolonged working condition.

This study aims to investigate muscle fatigue development and muscle alterations of either healthy or different MSDs diagnosed cases by using HD-sEMG. The main evaluation will be implemented via an electromyography manifestation, through EMG signal parameters, assessing on trapezius muscle. The experiment will be conducted while workers were working in the industrial prolonged working condition with heavily manual handling tasks, which is considered as one of the most major risk factor causing MSDs.

Workers who participated in this study will be selected from a production line that is suffering the risks of MSDs factors, as well as the availability of some found MSDs cases, diagnosed from medical methodology. These MSDs diagnosed cases would act as an experimental group, in order to find a correlation with the healthy ones, acting as a base line control group. All must work at the same production line and with the same task. The investigation of fatigue will be carried out for 4 periods of time, over each workday by 5 minutes each, including at the beginning of the day, before midday break, after resuming from the break and lastly at the relatively ending of the workday. The studied data collection period was not just designed for covering the whole workday, but it will also be conducted throughout the workweek. This intention aimed to determine the fatigue development both throughout the day-long (4 consecutive periods across the workday) and week-long (organized via two consecutive periods: the beginning of weekday and the ending of weekday respectively), as well as the correlation of both subject groups, the healthy and the MSDs case, and furthermore between the different MSDs affected muscle (focused only on upper limp muscle).

2 INTRODUCTION TO THE RELATED-MUSCLE FATIGUE PHYSIOLOGY AND ELECTROMYOGRAPHY FUNDAMENTALS

In this section, it is aimed to explain all relevant essential foundation, associated with this study. Regarding to, it would be helpful in order to provide comprehensive understandings and extensive views about this research for all readers, who may or may not have basic knowledge related to it. The explanation will be organized through several subtopics, which range from a basic principle issue, till up to the much more advanced ones, paving the way to step by step understanding, as presented consecutively as following.

2.1 Motor unit

It is the fact that in our daily life, since we are given birth, we all have been relying on muscle activities in almost all of our physiological processes, particularly for all of our dynamic movements, or even while being in none movement stage, including a voluntary static muscle contraction and an involuntary contraction such as cardiac muscle. Considerably, one of the most obvious examples could be: The new born infants generally cry and perform movements immediately just after being delivered.

Thereby, the basic concept of muscle system is then likely essential for whether a general knowledge or a specific one, such as for the study of the muscle fatigue-related electromyography content. The basically essential part of the movements controlling system in humans is so called motor unit (Farina et al., 2001a), which represents the functional and anatomical elements of the neuromuscular system. The motor unit mainly consists of a motor neuron and muscle fibres as demonstrated in figure 1 (Right picture).

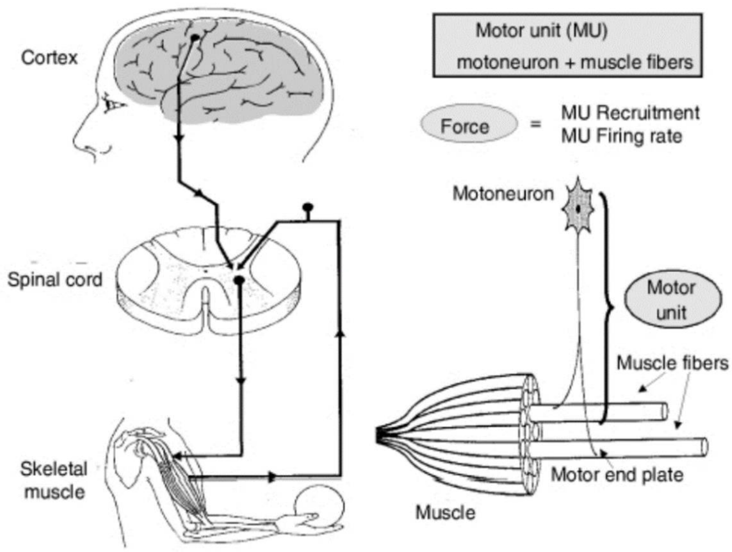


Figure 1. A schematic representation of basic motor control mechanisms and motor unit and its components (Sale, 1991, Roberto Merletti and Parker, 2004)

The motor units are not the entire source generating muscle activity processes yet, but they are just one part of the whole system, which essentially consists of a motor control and motor units. To be easier to have the idea of its function, it would be explained as following:

All of our muscle activities processes start from the brain portions: premotor cortex, the supplementary motor area, and other associated areas of the cortex (Roberto Merletti and Parker, 2004). The so called motor programing, containing all associated muscle activities orders, will travel from the brain to the particular active muscles through the spinal cord, which is considered as the first level of the motor hierarchy, also being the site of where motor neurons are located (Knierim, 2015). Then the motor programming will be transferred from motor control to motor units for allowing the innervation of muscle contraction, in order to perform the movement following the motor programing orders from the brain respectively. This system can be represented by a schematic of the integrated basic motor control mechanisms, motor unit and its components on figure 1. (Left picture), which would be able to give the reader more better comprehensive view.

As previously stated above, the motor unit (Farina et al., 2001a) plays a key role in muscle movement over its contraction, which obtains orders from a cortex of the brain via the electrical signals form (myoelectric signal). These electrical signals are subsequently transmitted from a motor neuron pool, located in a spinal cord to a particular active muscle by motor neuron, as shown in Figure 2. There is an one-to-one relationship between a motor neuron pool and an innovated particular muscle, namely all of motor neurons innovating a certain muscle are from the same motor neuron pool (Knierim, 2015) and generally a single motor neuron can innervate a set of muscular cells or so called set of muscle fibres.

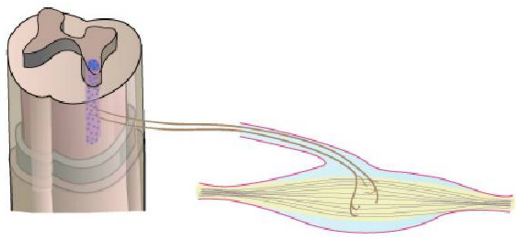


Figure 2. The connection between motor neuron pool and motor unit (Knierim, 2015) .

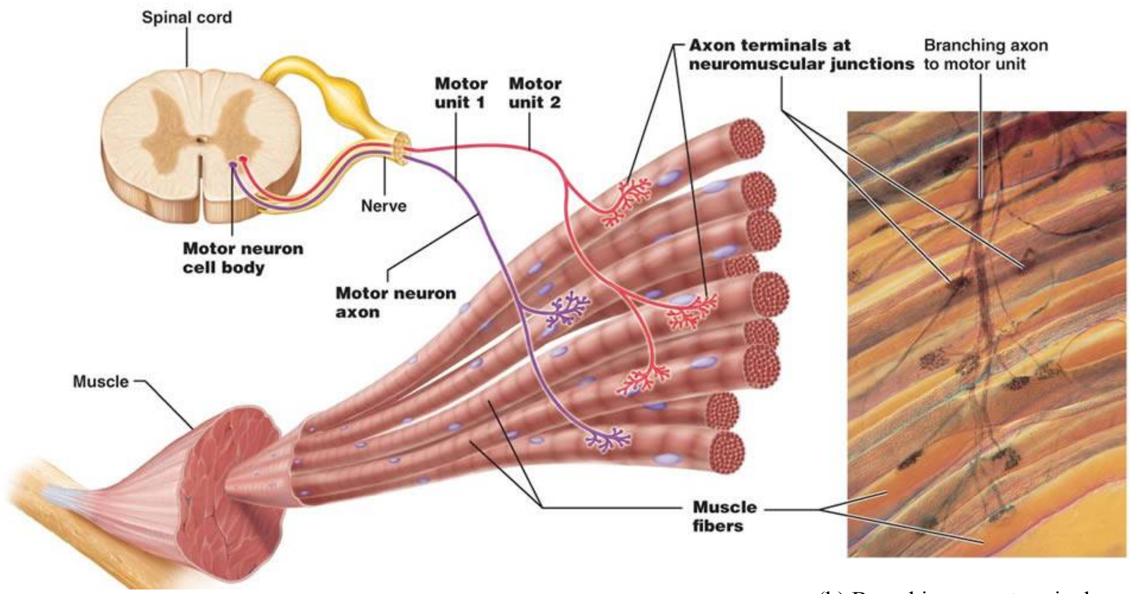
In general, a single muscle fibre has a diameter smaller than a millimetre, but it can be as long as several centimetres in length (Louis G. Tassinary et al., 2007). For having a greater comprehensive figure, the combination of an individual motor neuron and all innervated muscle fibres, which is called a motor unit, can be explained in figure 3. In humans, the number of MUs per muscle can vary from about 100 MUs for a small hand muscle up to 1000 MUs or more in large limb muscles (Warburton et al., 1999, Roberto Merletti and Parker, 2004).

The motor unit can be classified into three different types, based on physiological properties such as speed of contraction and fatigability (sensitivity of fatigue) (Roberto Merletti and Parker, 2004), as described as following details and in the figure 4 and 5.

1) Type I; with slow-twitch (S)

2) Type IIa; with fast-twitch, fatigue-resistant (FR)
3) Type IIb; with fast-twitch, fatigable (FF)

Type I (S) is the most resistant to fatigue, largely found in the red muscles, which hugely found for example in soleus (SOL) muscle. This type of the red muscle characterizes in various specific properties including: low ATPase, high capillarization, abundant hemoglobin, myoglobin and mitochondria for oxidative energy supply. Meanwhile, type IIb (FF) is mostly found in the pale muscles, which normally found for example in extensor *digitorum longus* (EDL). This type of pale muscle characterizes in various specific properties including: high ATPase enzyme for anaerobic energy utilization, low capillarization, less hemoglobin, myoglobin and mitochondria for oxidative energy supply.



(a) Axons of motor neurons extend from the spinal cord to the muscle. There each axon divides into a number of axon terminals that form neuromuscular junctions with muscle fibers scattered throughout the muscle

(b) Branching axon terminals form neuromuscular junctions, one per muscle fiber (photomicrograph 330x)

Figure 3. Motor units (Knierim, 2015).

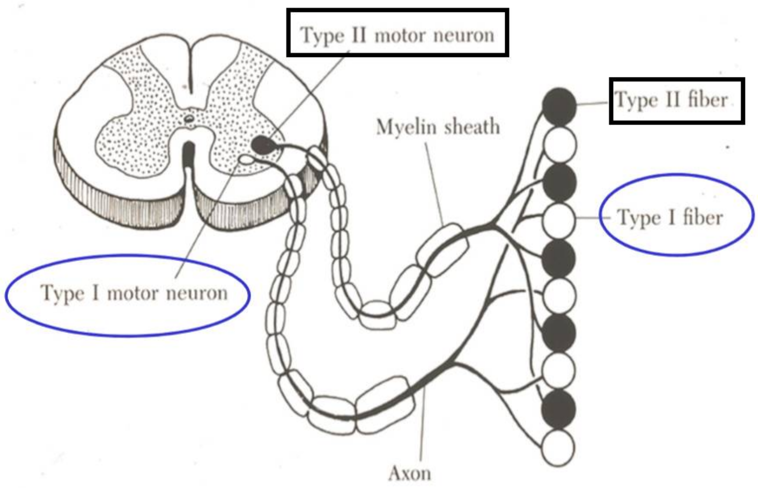


Figure 4. Motor unit of muscle fibres type I and type II (Brooks et al., 2000).

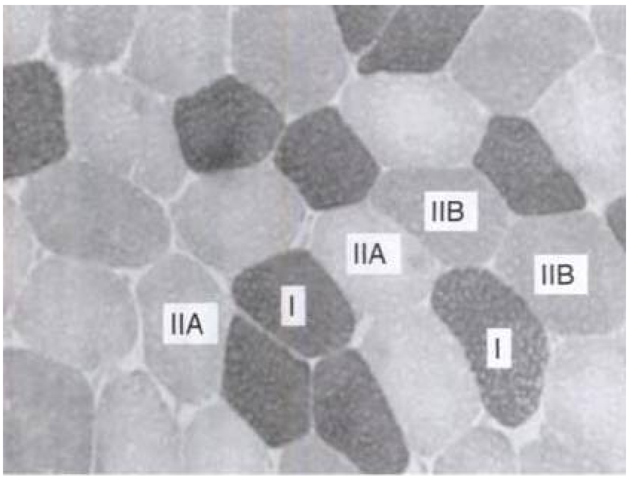


Figure 5. Histochemical determination of human muscle fibres (left) (Roberto Merletti and Parker, 2004)

2.2 Muscle fatigue

Muscle fatigue is a complex phenomenon. It could be caused from many possible reasons. So far, there had been many definitions or descriptions of muscle fatigue, which stated in several concepts, for instant: ‘‘failure to maintain the required or expected force” (Edwards, 1981), “Intensive activity of muscles causes a decline in performance, known as fatigue” (Allen and Westerblad, 2001), “Performing a motor task for long periods of time induces motor fatigue that is generally defined as a decline in a person’s ability to exert force” (Lorist et al., 2002). However, all these presented above are typically considered as definitions in just biomechanical viewpoint. However, there could be other definitions made particularly according to specific disciplines, for example in physiology viewpoint “fatigue is representing a failure of physiological system” (Green, 1997).

All these could roughly describe and give some related figures of what the possible muscle fatigue phenomena typically characterize. As a result of its complex phenomena, many linear models had been established aiming to explain the fatigue reaction appearing during the prolonged cycling movement. In this study, three main study-related models were selectively considered to be taken part in detailed explains, including: 1) Cardiovascular/Anaerobic Model, 2) Energy Supply/Energy depletion model, 3) Neuromuscular Fatigue Model. However, regarding to this study is associated relevantly involved in the neuromuscular system via EMG signals evaluation. Therefore, the Neuromuscular Fatigue Model was going to be more specially focused over the others, in which all details could be described respectively below.

2.2.1 Cardiovascular/Anaerobic Model

The cardiovascular/anaerobic model is mainly associated with the fatigue via a limit of working muscle performance. The essential principle is that the fatigue over working muscle will be occurring when there is insufficient oxygenated blood supplied to it, which is a result of the limit of heart function ability. Together with the ability of cardiovascular system that functions as facilitating a removal of accumulated metabolites out of the working muscle is also limited.

The limits take place when heart is no longer able to supply oxygen to the working muscle as well as the no longer ability of removing waste products back from the working muscle (Abbiss and Laursen, 2005). The associated factors involved with this issue could be roughly explained as:

a) Oxygen delivery and utilisation

Oxygen is one of the most necessary substances needed for establishing energy during the muscle activity. The more activity the muscle is doing, the more oxygen it needs. Cardiac output ability, which is reflected by a quantity of stroke volume and heart rate, is going to be gradually limited along the way of the maximal exercise period, and then eventually it will certainly be no longer able to pump blood, which functions as facilitating of oxygen carrying to and from destination organs, to the working muscle.

Occurring simultaneously with cardiac output, the red blood cell mass and plasma volume inside the delivery blood are also related to an effort spending muscle. Namely, more blood volume and/or red blood cell mass and plasma volume are also required in the working muscle. By which, the intensity of plasma volume could contribute to the reduction of oxygen content in the blood, regardless of the maintained haemoglobin content (Warburton et al., 1999). In response, more cardiac output is urgently requited to deliver more oxygen in need, however the ability of heart is limited depending on an individual training performance.

b) Metabolite accumulation

In addition, during the oxygen utilisation occurring in the muscle, it generates lactic acid that results in a lowering of a pH level of muscle and blood according to the dissociation of lactic acid into lactate and hydrogen ions (H^+) (Abbiss and Laursen, 2005, Brooks et al., 2000).

The muscle fatigue is believed to be due to the unbalance of production and removal process of metabolite accumulation. The hydrogen ions (H^+) is believed to play an important role in influencing pain receptors in the brain, inhibiting oxygen transportation via haemoglobin and reducing the dissociation of free fatty acid into the blood (Abbiss and Laursen, 2005, Brooks et al., 2000, Bogdanis et al., 1994). It is also hypothesized that the decreased intramuscular pH may lead to a decrease of glycolytic flux. In which processes through an inhibition of phosphofructokinase (PFK), consequently interrupting concentrations by reducing ca^{2+} release and removing ca^{2+} from the troponin, beside stimulating pain receptors and resulting to diminishing performance (Abbiss and Laursen, 2005, Brooks et al., 2000). The H^+ ions removal has been thought to be vital in fatigue reduction, which could be accomplished through an increasing speed of blood flow and skeletal muscle buffering capacity. However, some recent research suggests that the generation of lactic acid does not impair skeletal muscle function or efficiency (Santalla et al., 2003, Abbiss and Laursen, 2005, Brooks, 2001, Westerblad et al., 2002, Bangsbo et al., 1996).

2.2.2 Energy Supply/Energy depletion model

This model is a used to explain fatigue in an aspect of energy utilization in the working muscle. The model's driven key substance is ATP, which is standing for aerobic adenosine triphosphate, product by the mitochondria (Abbiss and Laursen, 2005). It is hypothesized that the fatigue is a result of an insufficient of the supplied ATP into an active muscle via various metabolic pathways (phosphocreatine re-phosphorylation, glycolysis and lipolysis) (Abbiss and Laursen, 2005, Green, 1997, Shulman and Rothman, 2001, Noakes, 2000).

Although, it is unclear about how much level of ATP that could be determined as a fatigue stage, but one hypothesis is being thought to have an influence in fatigue is that the perception of fatigue processed in the brain may come from the abnormal level of ATP sent by receptors (Abbiss and Laursen, 2005, Davis et al., 2000).

On the other hand, the energy depletion model is inversely explained against the energy supply one. Namely, the depletion of fuel substrate for example from: muscle, liver glycogen, blood glucose and phosphocreatine may cause the fatigue during the prolonged exercise (Abbiss and Laursen, 2005).

2.2.3 Neuromuscular Fatigue Model

Muscle fatigue is not just able to be defined via cardiovascular system or energy supply concept as described above, which most people may be thinkable. But there is also another model that plays a significant role in fatigue explanation. It is a neuromuscular fatigue model, considerably the most relevant fatigue related to the muscle fatigue scope being studied in this research. It can explain fatigue in very different ways which mainly involved in muscle excitation, recruitment and contraction, refer to electrical impulse sent from the brain. These factors do influence the muscle performance in exercise (Abbiss and Laursen, 2005).

In this principle, the fatigue occurs due to the failure of three main consecutive parts, which response in propagation of all movement commands on muscle contractions, all the way down through a pathway from the brain to working muscles. It is believed that this is a mechanism of preventing muscle fibre from badly damage. The three main consecutive parts of that path way are designated as different types of neuromuscular fatigue. They are considered based on the locations of the failure of the command chain on muscle contractions as shown in Figure 6.

From figure 6, it demonstrates neuromuscular fatigue models, which if consider along the pathway of signal travelling, it consists of three sequential models as described as following:

1) From the top of the diagram, it represents a central activation failure theory. It is associated to alterations in neurotransmitter concentration or being excited by afferent sensory feedback, which all contribute to a reduction in central activation.

2) From the middle of the diagram, it represents a neuromuscular propagation failure. This theory is associated to alterations in ionic pump activation and/or the motor neuron pool which contribute to a reduction of membrane excitability.

3) From the bottom of the diagram, it represents a peripheral failure theory. This theory is associated to the failure of the coupling function of actin and myosin that is believed to cause by calcium status while inhibition taking place in the muscle.

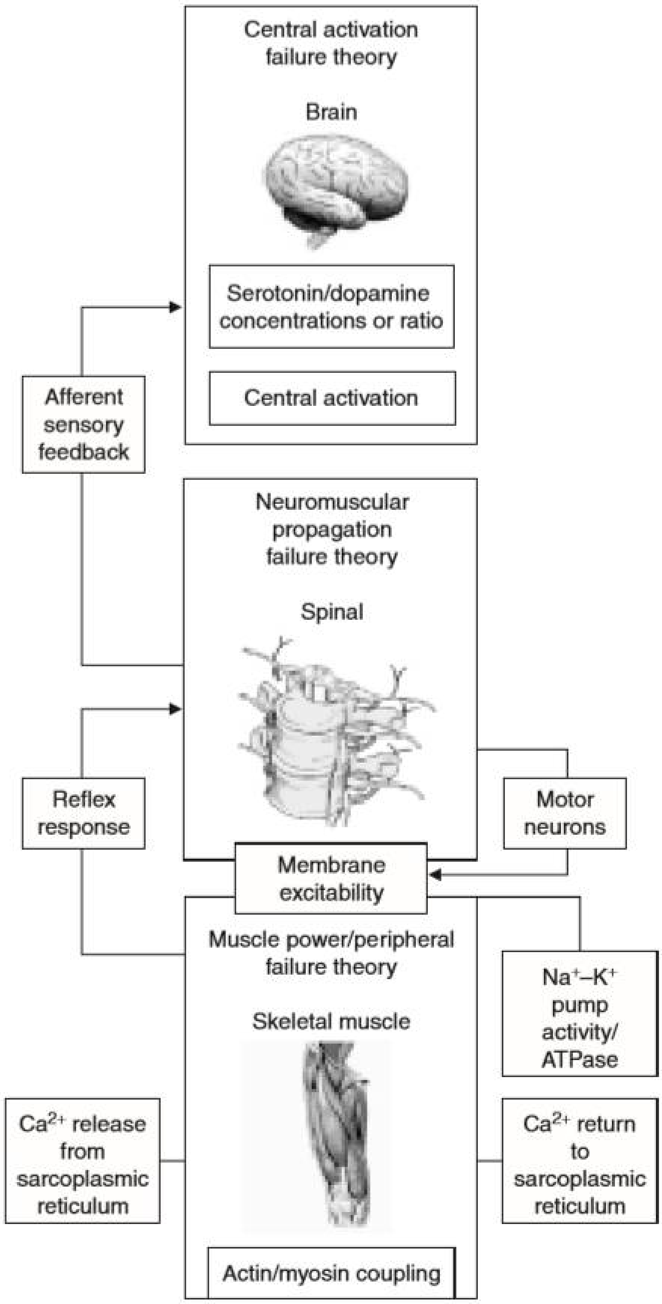


Figure 6. The neuromuscular fatigue models classified along the pathway of signal travelling

(Abbiss and Laursen, 2005)

a) Central activation failure theory

As mentioned earlier that any voluntary movement over muscles is generated from the brain before travelling all the way down, until reaching at the level of actin-myosin crossbridging of the active muscle fibres, via the neural system. The appearance of muscle fatigue can significantly be linked to the origin of that chain of the muscle activating process, namely from the motor centres in the brain. The failure of this muscle activating process occurring at the central nervous system (CNS) is associated to the fatigue phenomenal so called central fatigue. This failure is defined by the occurrence of a progressive decrease of muscle activation from the CNS through a decrease in neural input: the number of discharge rates of motor unit (Abbiss and Laursen, 2005, Allen and Westerblad, 2001, Allman and Rice, 2002, Boyas and Guevel, 2011, Blok JH et al., 2002, Davis and Bailey, 1997, Avela et al., 2001).

This reduction of neural input is believed to be one of the protective mechanism against the catastrophic damage of working muscle. The mechanism runs through a gradual built-up of intracortical inhibition, which in turn contributes to the development of pain that would be responsible to an alteration or avoidance of those involved working muscle utilization (Paasuke et al., 1999). Accordingly, the brain tends to decrease the rate of muscle excitement and recruitment, which is believed to be an influence of a built-up of serotonin and perhaps dopamine and acetylcholine concentrations in the brain, supposedly in response to the generated pain (Abbiss and Laursen, 2005, Davis et al., 2000, Davis and Bailey, 1997, Davis, 1995, Kay and Marino, 2000).

b) Neuromuscular propagation failure theory

As muscle works according to the excitation of neuromuscular propagation sent from the brain via neuromuscular propagation path way, the reduction in neural activation as well as the alteration in muscle action potential are hypothesised to be taking place during the prolonged exercise. Many researches indicated the place of this neuromuscular propagation failure is observed to occur at where a peripheral reflex response in the functioning muscles, which is actually in sarcolemma or α-motor neuron (Abbiss and Laursen, 2005).

The reductions in ionic (Na^+ and K^+) transmembrane gradients are believed to cause the inhibition occurring in those places (sarcolemma or α-motor neuron) (Green, 1997, Fowles et al., 2002, Nielsen and Clausen, 2000, Hamada et al., 2003). The reduction in neural activation, corresponding with the reduction in pH, is found in many ways including: reduction in action potential amplitude (obviously in sustained contraction), reduction in conduction velocity, reduction in frequency.

c) Peripheral failure theory

Peripheral failure theory can be described based upon the failure of excitation – contraction coupling mechanisms at actin-myosin contractile level (Abbiss and Laursen, 2005). It is hypothesised that Ca^{2+} reduction is the cause, inducing an appearance of this type of fatigue. As previously mentioned, the Ca^{2+} is a very important chemical substance for the muscle contraction process. During the prolonged exercise, there will be an increase of lactate anion and/or inorganic phosphate concentration that sarcoplasmic reticulum.

2.2.4 Myoelectric manifestation of muscle fatigue according to neuromuscular failure theory

As the central nervous system controlling muscle force by varying the activities of the motor units via motor neuron innervation, which is achieved through a set of muscular cells or so called muscle fibres, the electrical signals transmission seems to play a key role over the process. Those electrical signals (motor programming), travelling from the brain to the particular active muscles (muscle fibres) through the spinal cord, can simply characterize just as same as any other electrical signals, but they are in supper small amplitude, namely in just about in the range of micro volt.

The motor unit action potential (MUAP) is the so called representative of those electrical wave forms, which are being innervated and travelling through the active motor units. The MUAP represents several muscle behaviours related to muscle fatigue, which are mixed together electrically. Therefore, if we can detect and measure/record them, the chance of understanding the ways they response to physical muscle fatigue, which is possible by signal analysis, is obviously looming ahead.

However, in order to obtain that, it is necessary to extract them off via the advanced mathematical methods. The first step to obtain those EMG wave forms is to use electromyography (EMG) detecting/recording instrument to detect, acquire, amplify, and record as much information as possible in order to obtain as much raw EMG signal as it could be. There are two techniques available for that kind of accomplishment which consists of: detecting right inside the muscle fibres underneath the skin or so called intramuscular technique and another type is detecting on the surface of skin, where is being under investigation or so called surface EMG technique.

As known from the above description, once the increase of lactate concentration occurs, the intracellular pH will change by decreasing during the muscle fatigue. This phenomenal contributes to a decrease in muscle fibre conduction velocity (CV), which plays an important role of influencing a power spectrum frequency, tending to be compressed and shifting toward a lower frequency direction. On the other hand, it contributes to the increase in amplitude of electromyography signals in surface EMG technique, but decrease in an intramuscular technique. This contrary appears due to the tissue acts as a low-pass filter, and then allowing more energy to reach surface electrode (Basmajian J.V. and De Luca C.J., 1985).

For more comprehensive insight, one of the best example is in figure 6 presented below, it demonstrates the tendency and relationship of the dominant EMG parameters, consisting of amplitude-related, frequency-related and velocity-related parameters, measured by surface EMG technique during a sustained isometric contraction.

Nowadays, regarding to its useful application, the myoelectric manifestations of muscle fatigue is widely being interested in various fields, for example, in medical, sport or ergonomic affair etc. Many more researchers had turned their attention to its related-investigation. This had led to the continuous intensive research and developments over this related technology and technique, which consequently contributed to the more advanced in application and the more precision in muscle fatigue evaluation.

However, most of the researches having been conducted were still likely from the sustained isometric contraction type, set up in the strictly-controlled laboratory. This may hint to the fact that there is still more attempt needed to be made in order to prove its capability, particularly in the practical ways of application, which could be very helpful in applying in the real-world working condition soon later.

The multi-channels surface EMG or so called high-density surface EMG is now the most shining in this research area (typically in the non-invasive technique), due to its properties that superior to the conventional one (a single mono-polar or bi-polar surface EMG). Although, it is not designed to replace the intramuscular technique that is usually utilized in the medical affair. For more details about the high-density surface EMG and all basic fundamental, which is necessary for enhancing readers knowledge, can be described over different sections below.

2.3 High-Density surface Electromyography

In this section, it is aimed to explain any important knowledge, essentially related to high-density surface electromyography, which was a major research tool in this study. The main purpose is to provide the comprehensive understanding and extensive views of this study. The explanations will be organized through several subtopics that are considered necessary for any reader, whether who is having its background or not. Regarding to, they are arranged from related basic principles to the more advanced ones step by step, as presented consecutively as following:

2.3.1 Introduction to electromyography equipment

Electromyography instrument can basically be classified into two different types, including intramuscular electromyography measurement or so called invasive technique and the surface electromyography measurement or so called non-invasive technique. This classification is based on its physical measurement method principle, which is according to its EMG signal measurement location. Each one comes up with its own advantageous properties, suitable to different kind of EMG assessment's purposes, which needed to be properly selected for such particular job. For more detailed information, it is going to be described as following.

2.3.1.1 Intramuscular electromyography (Invasive technique EMG)

Intramuscular electromyography signal recording so-called invasive technique was first introduced by Adrian and Bronk in 1929 (Henneberg, 2000). This technique of EMG assessment is mostly utilized as diagnostic tool in clinical neurophysiology, assessing through measuring of EMG signals during voluntary activity, particularly in patients with neuromuscular disorders (Drost et al., 2006). However, it is considered as a painful procedure and inconvenient measurement type, particularly for the children clinical examination, sport or ergonomic (Merletti et al., 2008, Drost et al., 2006). Regarding to, its simply requirement of an insertion of needle electrodes into the muscle fibres as shown in figure 7, therefore making this technique provide pretty much high accuracy of the EMG investigation. It is a result of its EMG signal detecting's location that is right inside the source of the EMG activation (active muscle fibre) itself. Consequently, the quality of the detected signals become pretty high and much accurate, due to the result of its own unique property in limiting of diffusion effect (Merletti et al., 2008).

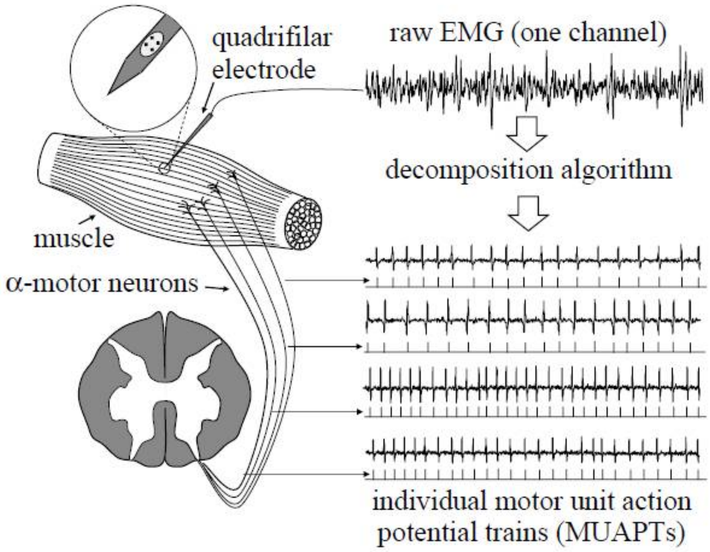


Figure 7. Schematic representation of the detection and decomposition of intramuscular EMG signals (Merletti and Farina, 2009).

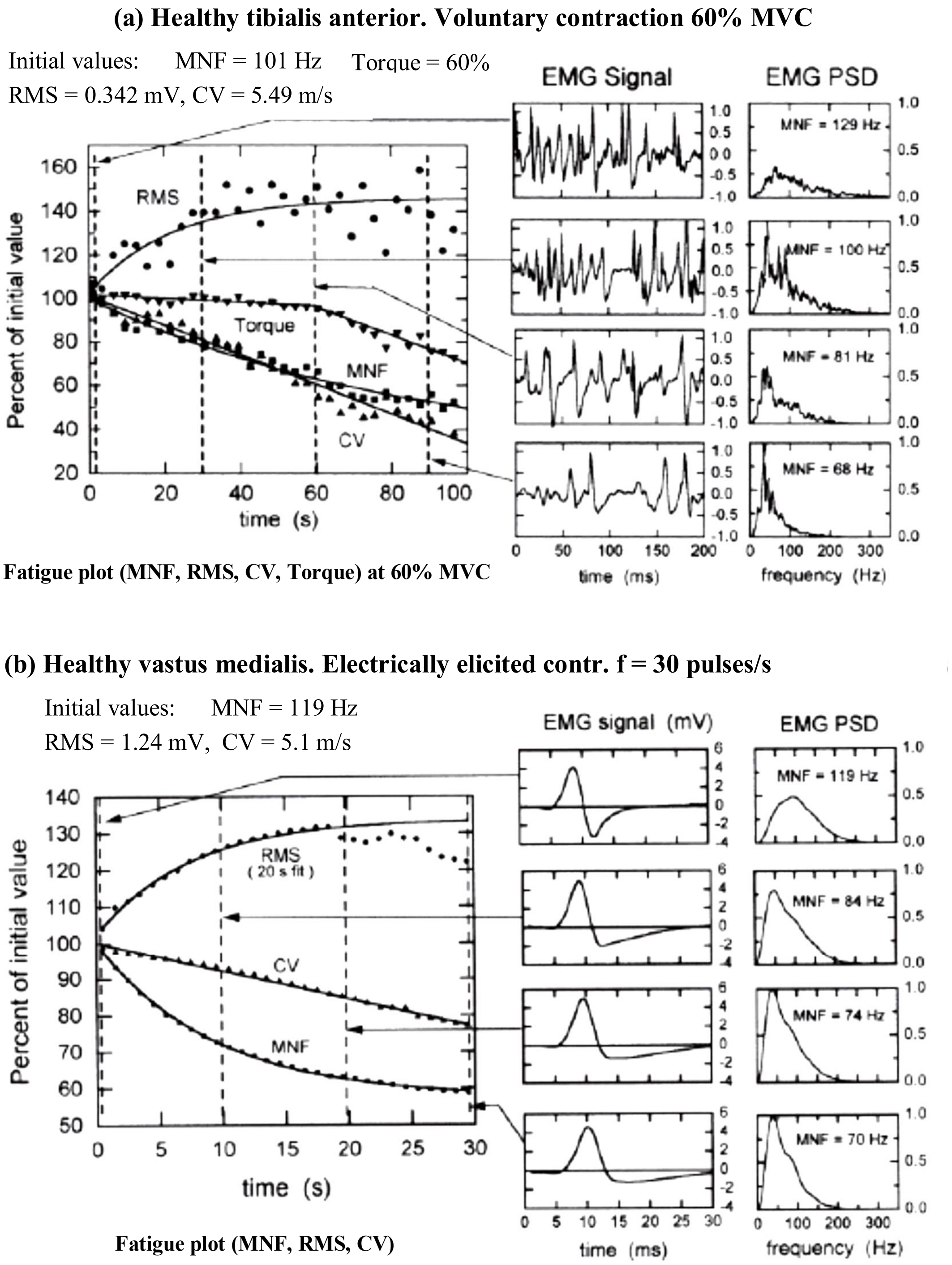


Figure 8. Demonstrating some examples of fatigue plots showing the time course of EMG signal variables during a sustained contraction over the EMG signal and its power spectral density (PSD) during specific time windows. All obtained from (Merletti and Lo Conte, 1997)(Cifrek et al., 2009).

2.3.1.2 Surface electromyography (Non-invasive technique EMG)

Non-invasive technique EMG assessment is the technique, that doesn't require the procedure of an insertion of any needle, but instead, it requires the employment of sensory electrodes to locate and place over the particular active muscle portion being investigated. This technique is also known as surface EMG technique, emerging entirely with no intention to replace the invasive technique application at all, which is typically utilized as diagnostic tool in clinical neurophysiology. It had widely been becoming attractive among people, who were working in this field, regarding to its unique properties in detecting and measuring the EMG signals, which is capable to be extracted into various crucial information, whether the one related to muscle activation, neural control strategies or neuromuscular system properties (Merletti et al., 2009b).

This extracted information, via different EMG parameters as shown in figure 8, could be beneficial in various different fields, particularly for instance rehabilitation medicine, ergonomics, sports medicine, physiotherapy, neurophysiology and kinesiology. They could be utilized in many applications such as the ability to monitor movements and neuromuscular control, to assess muscle changes due to aging, pathology, therapy, training, immobilization, lack of gravity, occupational disorders, etc. (Roberto Merletti and Parker, 2004, Merletti et al., 2009b).

From figure 8, it demonstrates some examples of fatigue plots showing the time course of EMG signal variables, assessing during a sustained contraction on the EMG signal and its power spectral density (PSD) at the specific time window. The details consist of: (a) showing a voluntary contraction of a healthy tibialis anterior muscle sustained at 60% MVC last for 100s. A three point moving average has been applied to the variables and one value every 3 s is displayed, this is due to the purpose of clarity, and noticeably with the mechanical breakpoint at 60s. (b) Demonstrating a healthy vastus medialis electrically elicited contraction stimulated for 30s at 30 pulses/s. All shorten parameters mean: MNF = mean frequency of the PSD, RMS = root mean square value, CV = conduction velocity.

The surface EMG technique can roughly be classified by considering the number of channels and electrode array dimension as: a single differential channel surface EMG or so called bipolar surface EMG and the multi-channel surface EMG. The bipolar surface EMG has a simple configuration and could be considered as a classic conventional EMG device as shown in figure 9. While the multi-channel surface EMG has pretty much more complex configuration, it can even be distinguished into: one-dimensional surface EMG and two-dimensional surface EMG as shown in figure 10.

Over a past decade up to the time of this literature writing, the researches tendency had rather moved toward the multi-channel surface EMG, particularly for the two-dimensional one than the conventional single differential channel one. This is apparently the result from many advantageous points of it over the conventional one, consisting of its larger detected skin area, provided by the larger array of two-dimensional surface EMG sensors, which is placed right overlying the investigated muscle. By this, it contributes to an increase in efficiency on the MUs characteristics detection, not only for the temporal information, but also for the spatial distribution of the electrical activity over the muscle being examined (Blok JH et al., 2002, Stegeman et al., 2000, Drost et al., 2006, Merletti et al., 2003).

So far, there had been a number of studies conducting to investigate the muscle fatigue, by using the classic bipolar electromyography (EMG) electrodes, applying over a tiny area of muscle portion. Considerably, with the complexity of a surface EMG signals extraction, this may have resulted in only simple tasks were consequently considered to be taken into account (Farina et al., 2004b). Furthermore, those studies were mostly conducted in the laboratory experiment setup, with only small number of studies that were achieved in the real industrial sectors or in the real-world activities. This fact may have been due to the assessing muscle fatigue in the real-world working condition is too much more complicated than in the experimental ones.

The main obstacles of this limitation could be from many factors as explainable by consisting of: firstly, due to the artefacts generated from the movement and vibration on the fixed dry inter-electrode, located over the skin during the dynamic contraction. Secondly, due to a non-uniformity of motor unit distribution that changes rapidly over time of the repetitive movement, depending on the different location within the muscle (Falla et al., 2006). Thirdly, regarding to the ongoing production line, which may have contributed to the restriction of some measurement procedures, prompting the measurement is not as smoothly as the setting up in the laboratory one.

Therefore, the utilization of the conventional bipolar surface EMG electrodes, which is considered with less efficiency than the multichannels surface EMG, could have ended up with a high variance of the EMG variables, and may even be contradictory in results (Falla et al., 2014b), according to its very small detected area over the tiny portion of muscle. This is also in agreement with some other studies, that revealed the very high variance of the estimation, using a few channels of surface EMG electrodes, that could limit the practical application (Farina and Falla, 2008a). In order to cope with those kind of obstacles, it is more suitable and recommended to utilize the two-dimensional surface EMG or so called hi-density surface EMG in this kind of job. Regarding to, not only all of its more greatly advanced advantages over the conventional one, as already described above, but it is also specially designed to work along with its semi disposable adhesive linear arrays, which makes the measurement during the dynamic movement more suitably functional. This disposable adhesive linear arrays will be working alongside the EMG electrodes grids, separating the electrode grid metal sensors from subject's skin, but still maintain the electrical conductivity through the small cavities, filled with 20-30 µL of conductive gel.

By this superior property, it will allow action potentials, travelling along the muscle fibre during the dynamic contraction to be directly detected efficiently (Farina et al., 2004c), with less variability and high reliability (Farina and Falla, 2008a, Farina et al., 2001a, Farina et al., 2004c, D. Farina et al., 2004, Troiano et al., 2008), during the fast-paced and repetitive movement. However, with some reasons so far, most of the studies still had been conducted in the experimental laboratory setup and mostly through the simulated work tasks, with quite limited short time period.

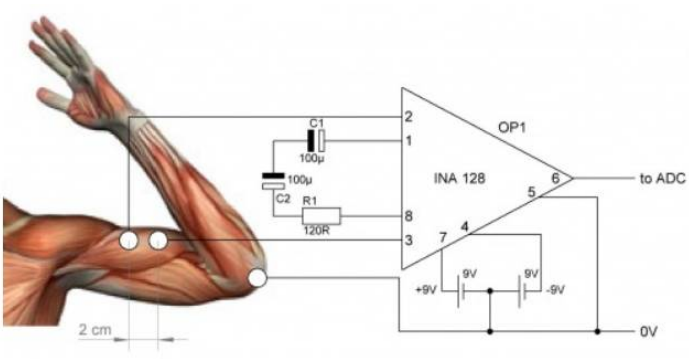


Figure 9. Bipolar surface EMG circuit diagram (GitHub, 2015).

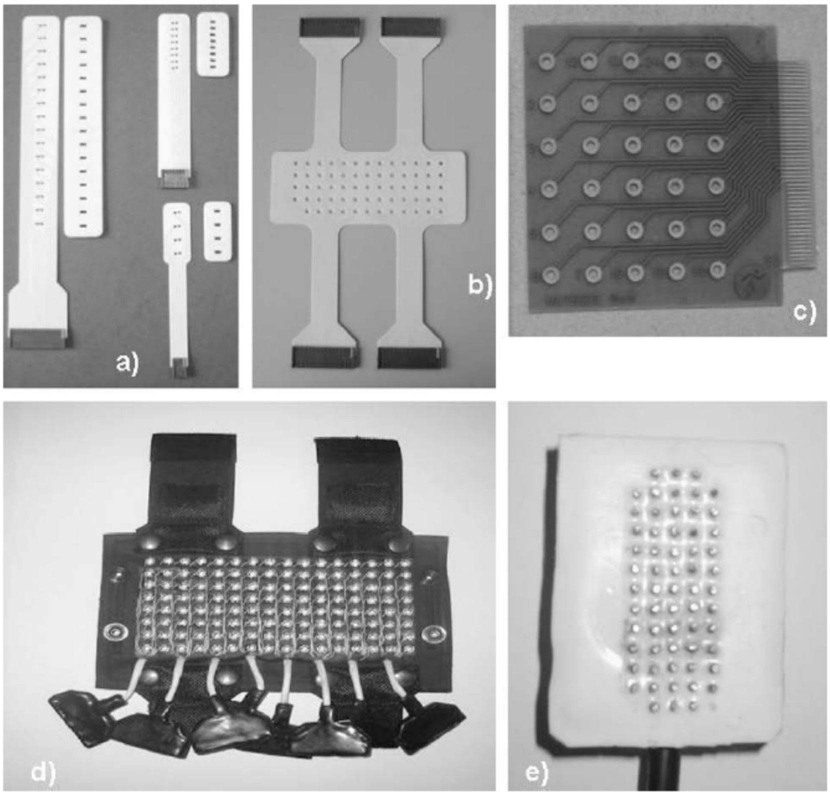


Figure 10. Various types of surface EMG arrays electrode. (a) Examples of linear electrode arrays with different electrode numbers and inter electrode distances. The cavities in the double adhesive foam are filled with gel, through the holes in the arrays, after positioning. (b) An example of a two-dimensional flexible electrode grid (LISiN-Spes Medica, Italy) with 64 electrodes. (c) A Printed circuit bi-dimensional electrode array of 6×5 electrodes on Mylar. (d) The 128 silver coated eyelets on a textile support, with eight columns and 16 rows of electrodes. (e) The bi-dimensional pin electrode array of 61 silver electrodes, with five columns and 13 rows of electrodes (1 mm diameter, 3-mm inter electrode distance in both directions) without the four corner electrodes (Merletti et al., 2009b).

2.3.2 Fundamental components of surface EMG acquisition system

Regarding to the myoelectric activity, involving in muscle activities activation is extremely very small in term of electrical signals amplitude. Their amplitudes generally could be ranged from some a micro to a few milli-Volts peak-to-peak, depending on the intensity of muscle contraction (Garcia and Vieira, 2011).

The detection of this very small signal, requires a very sophisticated sensitive instruments, regarding to a complexity of the skin nature, acting as low pass filter which allows a specifically limited range of frequency bandwidth of approximately between 15 to 400 Hz to pass through (Garcia and Vieira, 2011). The involving signals obtained from the measurement could be not only from the muscle being investigated, but it could be contaminated from other possibly source as artefact's frequency, that may interfere this myoelectric activity as well. All these complexity of EMG measurement could be accomplished through the set of equipment described through a simplified block diagram, as presented in figure 11. It demonstrates a set of a block diagram showing each of main steps of surface electromyograms acquisition procedure including: (1) the detection of myoelectric potentials with surface electrodes and a reference electrode, schematically illustrated on the medial epicondyle of the humerus; (2) the amplification of such potentials with differential amplifiers; (3) an analog filtering of the amplified potentials, designing to avoid aliasing and, finally; (4) the sampling of the surface electromyogram into digital voltage values, in order to be stored on a computer (5) (Garcia and Vieira, 2011).

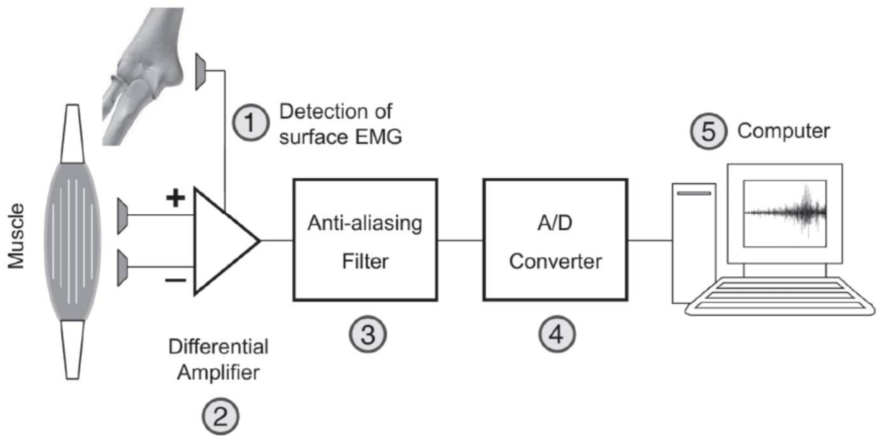


Figure 11. Demonstrating a simplified block diagram of surface electromyogram acquisition (Garcia and Vieira, 2011).

Regarding to the simplified block diagram of the surface electromyogram acquisition presented above, it demonstrates 5 major acquisition steps consecutively, including: step 1 detection, step 2 amplification, step 3 conditioning, step 4 digitization and lastly step 5 storage. Each step has its own important function as separately described as following:

The detection step plays a key role in detecting the electromyography signals throughout the surface EMG electrodes, whether via a monopolar, bipolar or multipolar surface EMG, depending on what is the selected application. Anyway, this step requires the placement of a reference electrode, which is generally going to be positioned on a bony portion, such as wrist, in order to prevent the major investigated EMG signals from any other interference muscle activity.

As mentioned above, the detected electromyography signals are very extremely small, therefore, the second step as amplification will play a major role in amplifying of those extreme small detected signals to become relatively much bigger. It is going to be accomplished through a differential amplifier, multiplying the difference between two voltage signals by a constant value of the amplifier gain, which is very crucial for amplitude in correspondence to the dynamic range of the A/D converter in step 4 (Garcia and Vieira, 2011). This amplification step is very necessary to be completed before a digitalization process in step 4, Due to the dynamic range of A/D converter in electromyography systems varies from ±2.5 V to ±10V (Garcia and Vieira, 2011), otherwise the digitization process would not be able to capture such extremely small fluctuating raw electromyography signals, picked up from the activity of MUs (Garcia and Vieira, 2011). Considerably, in a concern about an interference of power line, presented by the unbalanced impedances in electrode-skin interfaces and high CMRR, the amplifiers must be designed with high input impedance, or namely should be greater than mega-ohm (Garcia and Vieira, 2011), in order to reduce this noisy interference in the first place.

The amplified electromyography signals having been processed from step 2, will be treated by the conditioning step 3. This step will operate as low-pass analogic filters. Its main function is to suppress the phenomenon, that is known as aliasing, occurring during analogic sampling process at the rates smaller than twice their designed highest frequency (for example less than 800 samples/s for the surface EMGs) (Garcia and Vieira, 2011). The sinusoids with frequencies above this threshold are superimposed on the low frequency sinusoids.

After the process of the conditioning step 3, the electromyography signals will be going through the digitization process, accomplished by A/D converter in step 4. Its main function is to convert the sampled analog signals into the digital one, in order to achieve the storage completion with a digital format file in step 5. After the entire processes completed, it is possible and highly recommended to remove the undesired components from the recorded digitized surface EMG signals, which for example could be contaminated by some movement artefacts with the frequency below 20Hz.

This re-filtering process can be achieved by using the digital filtering process, that usually apply a band-pass filter of about 10 – 500 Hz in bandwidth, which in this research it was going to be accomplished digitally through a MATLAB programing.

2.3.3 Electrodes and examined skin preparation for surface EMG acquisition

In term of surface EMG measurement, the electrodes and skin preparation are pretty important, in term of a close cooperation to each other. The quality of the recorded EMG signals are highly dependent on the relationship of the two, due to both cooperation help enhance the chance of picking up as accurate raw signals as possible, in term of sensors and skin interfacing. In this section, it was aimed to explain essentially all relevant aspects associated to this issue. The electrode classification, Electrode-skin impedance and skin preparation for surface EMG, and Electrode montage recording configuration will be demonstrated consecutively as following:

2.3.3.1 Electrode classification

A surface EMG electrode characterizes as transducer of ionic current, detecting and capturing the ionic current from flowing in the skin tissue via metal wire, all are achieved by the electronic instruments, which on the other hand, it is also possibly to be defined as the sensor of the electrical activity of the muscle (Merletti et al., 2009b). The surface EMG electrode can be classified into two main different types: dry electrode and non-dry or wet electrode, based on the basis of material and manufacturing technologies (Merletti et al., 2009b).

The dry electrodes are generally in the form of bar or pin feature, with the materials made from whether noble metals (e.g. gold, platinum or silver), carbon, sintered silver or silver chloride electrodes. Meanwhile, the wet electrodes are made generally from all those previously mentioned electrodes, but they are additionally combined with whether layer of conductive gel, hydrogel or sponge saturated with an electrolyte solution. Considerably, they are usually designed as self-adhesive, which is very suitable for the dynamic movement analysis of surface EMG (Merletti et al., 2009b). On one hand, using the dry electrodes type with dynamic movement assessment may be contributing to some movement artefact, which could typically introduce to 20 Hz or lower occurrence. This may partially interfere the lower frequency component of surface EMG signal, normally ranging between 10 – 500 Hz, causing loss of some recorded important raw information.

The electrode that was selected to use in this research was a wet electrode type D, as demonstrated in figure 12. Regarding to its most suitable properties that comes up with the conductive gel and self-adhesive, efficiently cooperating with the rigid electrode arrays made of Ag-AgCl, which truly provide the lowest noise of electrode-skin interface (see section 2.3.3.2) and is recommended for surface EMG recording (Freriks B. et al., 1997).

In conclusion, with the entire components (The same components which were used in this research study) including electrode material, conductive gel, self-adhesive properties, it is therefore establishing highly stable, lower noise level and suitable for surface EMG recording, particularly in dynamic movement (Merletti et al., 2009b).

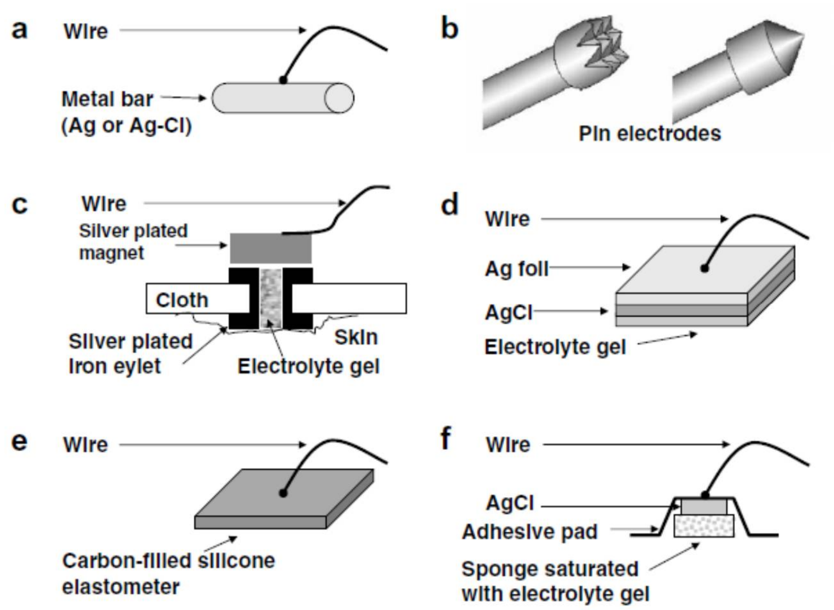


Figure 12. Examples of surface electrode types for EMG recordings: (a) solid metal bar electrode (dry); (b) pin electrodes (dry); (c) eyelet on cloth with magnetic connector (wet or dry); (d) disposable Ag–AgCl electrode (wet); (e) carbon-filled elastomer electrode (dry); (f) disposable electrode with sponge saturated with an electrolyte gel (wet) (Merletti et al., 2009b).

2.3.3.2 Electrode-skin impedance and skin preparation for surface EMG recording

The skin in a surface EMG recording content is considered as the sources of surface EMG signals. The skin can be considered as an interface between a multi-layer, conductive, non-homogeneous, and anisotropic substrate (epidermis, derma, subcutaneous layers, blood vessels, fat tissue muscle and insulating substrate (air)) (Merletti et al., 2009b) as shown its model in figure 13.

Since the process of surface EMG recording is an electrical matter, thus all related components, whether form the instrument itself (hardware and software) or from the source of EMG signals (skin's layers and tissue) can be considered as one of electrical components and can be included in an electrical circuit for any electrical calculation. Therefore, with the electrode selected in this research is wet type electrode of Ag-AgCl, working alongside self-adhesive and conductive gel (type D in figure 12), so the skin and its components can be modelled as an electrical equivalent circuit through a non-linear RC circuit, which consists of two main consecutive portions: electrode-electrolyte interface and electrolyte-skin interface as shown in figure 14. From figure 14, portion (a) shows a simplified electrical model of the electrode–gel interface including: E_{hc} representing the half-cell potential at the metal–electrolyte junction, the parallel R_pC_p representing the polarizability and the capacitive behaviour of the junction, the R_s describing the resistive behaviour of the electrolyte gel, and the V_{noise} representing associated noise component. Portion (b) shows a generalized model of the electrode – skin interface consisting of:

the electrode–electrolyte junction, having already been described in portion (a) consisting of R_p, C_p, and R_s, and the electrolyte-skin interface containing of: [E_{epi} representing the half-cell potential due to differences in the ionic concentrations between the gel and the superficial layer of the skin], [the parallel $R_{epi}C_{epi}$ characterizing the skin impedance], and [R_{sub} representing a resistive component associated to the subcutaneous tissue layer]. The equivalent noise generators are not indicated due to simplicity purpose, but are present at all interfaces. (Merletti et al., 2009b)

Dermis

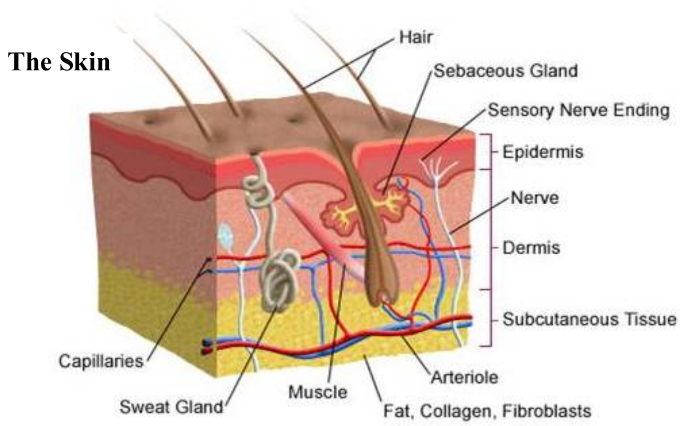


Figure 13. Demonstrating skin components which are considered as the interface between a multi-layer, conductive, non-homogeneous, and anisotropic substrate (epidermis, derma, subcutaneous layers, blood vessels, fat tissue muscle and insulating substrate (air)) : The photograph obtained from (Ternopil state medical university, 2015).

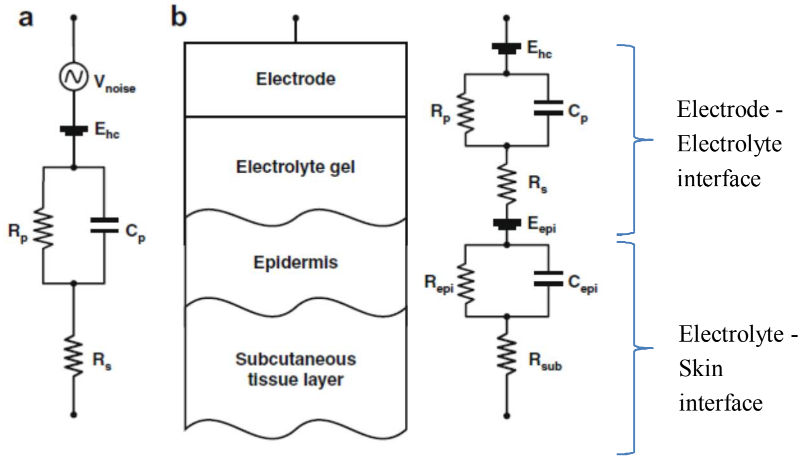


Figure 14. Demonstrating models of the electrode–skin impedance, all were Re-drawn and adapted from Neuman (1998) in (Merletti et al., 2009b)-

In order to obtain the highest quality of EMG signals as possible, the skin surface treatment is significantly important to be taken into account (Clancy et al., 2002, Huigen et al., 2002, Merletti et al., 2009b). It is possible to be accomplished by reducing the electrode-skin interface impedance, through the skin preparation process prior to the electrodes placement. The process can be conducted by starting to be observing subject's skin at the marked point, if it is covered with excessive hair, it may have to be shaved before the attachment, in order to ensure a strong bond of sensor interface and better electrode contact with the skin, but if it is covered with acceptable pretty less hair, this particular skin may not be necessary to be shaved. Afterward the skin observation, then apply some alcohol onto the marked area, cleaning and allowing it to be completely vaporizing, so that the skin would be drying, before applying the conductive and abrasive paste, which is especially made for reducing the skin impedance during the EMG measurement. After all, place the electrode arrays onto that marked area of the investigated muscle, and secure it to the skin as firm as possible by adhesive tapes, in order to ensure that this array of sensors will not be losing or shifting off the marked area during the whole long recording period.

2.3.3.3 Electrode montage recording configuration

As described in the above subtitle the electrode and skin preparation, it revealed that there are many factors needed to be considered, for which are associated with the efficiency of the surface EMG signal recording. However, there is still another remaining factor left, which also plays an important role in this issue. It is an electrode montage, or in the other word: the configuration of electrode. It could generally be categorized into two different modes: monopolar configuration and the bipolar one.

The monopolar mode is responsible to detecting the MUAPs electrical potential, exactly and instantly on the skin above the investigated muscle tissue, where those electrodes were deployed, with respect to the reference electrode, located at bony regions on the skin. In this research, the reference electrode was located at a wrist on the same side of the investigated upper trapezius. By these, the MUAPs electrical potential measured from the mono-polar mode clearly become the precise actual surface potential that is occurring at the moment of the measurement and containing all the information from the investigated MUAPs electrical potential source, which is situating right in the muscle tissue beneath the electrodes (Garcia and Vieira, 2011).

Although it might also record some interferences, from outside sources, for example from power line, or from distant muscles, or known as crosstalk (Garcia and Vieira, 2011). All these involving interferences are not unexpected to be seen occurring, regarding to its nature of measuring in the real life working environment, namely it is likely almost impossible to prevent those from occurring even hardly in an ideally experimental setup one.

There are two countermeasures against this issue. In order to minimize those interferences, it is possible to be doing it through a specific signal treatment, since we know the frequency of the surface EMG signals activity, which ranges between 10 – 500 Hz (SENIAM), thus it is able to be accomplished over two consecutive steps: The first one is the Anti-aliasing filtering step, which is generally conducted via hardware activity during the recording process, as shown in figure 11. The second step is the one, which is able to be accomplished by the digital filtering once again, prior to the signal processing of all EMG parameters calculation processes. Which in this study, it was conducted via MATLAB programming.

Meanwhile, the bipolar configuration will work on the principle of detecting all of the difference potential, occurring between the two electrodes, located at a fixed distance (inter-electrode distance; IED), which are necessarily placed along the muscle fibre direction (Merletti et al., 2009a). Considerably, there is a difference of electrical potentials detected by each electrode of the bipolar one, consisting of two monopolar electrodes, located at a fixed distance (inter-electrode distance; IED), as demonstrated in figure 15. From figure 15, two electrodes are positioned at the skin locations above the muscle tissue, whereas a reference electrode is located on the skin close to bony regions. The monopolar EMGs represent the single fibre action potentials detected by each surface electrodes, which can be demonstrated on the top right. Each EMGs (traces 1 and 2) represents the difference between the electrical potentials detected by each surface electrode and its reference one (presumably zero). The bipolar EMG signal (trace 3) is obtained from the more complex differentiating step of the potentials among those two monopolar EMGs (traces 2 and 3). The dashed vertical lines (t1, t2 and t3) indicates times when the difference between traces 1 and 2 is maximal, zero and minimal respectively. By these, it is obvious that, signal No. 3 is a result from a difference of the potentials between signal 1 and signal 2, characterizing as a monopolar configuration. Therefore, in conclusion, signals that obtained from the bipolar configuration are not exactly the instant MUAPs potentials, occurring at the locations, where those electrodes were deployed.

Remarkably, since the bipolar configuration detects signals based on a differential signal principle of two monopolar, it is likely that, crosstalk phenomenal could be consequentially reduced afterward. This is as a result of each monopolar, that trends to detect over very similar amplitudes of any interfering sources, whether crosstalk generated over distant muscle, from deep MUs located in the muscle being evaluated, or even from the power line interference. With these, the resulted signals appear to be fairly attenuated, according to the nature of a differentiated signal (Garcia and Vieira, 2011). By considering this phenomenon, it seems that, the bipolar electrode is more advantageous over the mono-one, due to the benefit of attenuating of the interference signals.

However, it remarkably does not attenuate only the unwanted interference signals, but it also attenuates the detection volume of the essential raw EMG signals, which is the crucial original information for EMG parameters calculation (Gabriel, 2011, Garcia and Vieira, 2011, Staudenmann et al., 2005b). Moreover, its placement details and location of electrode arrays are very important essentially for this configuration, since each differential output signal requires the reference potential from the electrode, located before it consequentially, so the alignment of all consecutive electrodes must necessarily in the same line or parallel with muscle fibre, and selectively with the same direction of muscle fibre alignment, where MUAPs are travelling along that direction only.

According to this restricted applicable condition, it may contribute to a problem in an EMG based force estimation, especially for dynamic movements on the contexts of an electrode movement and the force-length-velocity relationships of muscle (Staudenmann et al., 2005b). In addition, if in case of two surface electrodes located symmetrically right at each opposite side of the innervation zone (IZ), it is possibly that, as the action potentials propagate along each opposite direction of IZ, each surface electrode would record the same Mono-polar potential at the same time, thus the contributions from this MUs would not appear in the form of differential EMG (Garcia and Vieira, 2011). Therefore, it is not surprising that several studies suggest the location of the bi-polar detection system to be only over somewhere between the IZ and the tendon region (Troiano et al., 2008, Farina et al., 2002a, Garcia and Vieira, 2011, Merletti et al., 2003, Rainoldi et al., 2004, Rainoldi et al., 2000).

Furthermore, Staudenmann and colleagues (Staudenmann et al., 2005b) conducted the experiment to examine the optimal configurations of multi-channel EMG electrode arrays in muscle force estimation, between mono-polar and the bipolar one. The set up experiment was for measuring the signals obtained from triceps *brachii* muscle, contracting during the elbow flexion and extension. They found that, the signals, obtained from mono-polar configuration (13×10 electrode arrays) were observed in very homogeneous patterns, and significantly more homogeneous than the one observed from the bi-polar configuration (12×10 electrode arrays) as shown in figure 16.

From figure 16, it shows that all EMG signals increased simultaneously with an increase in force. The signals obtained from 13×10 monopolar montage (left panel) showed a strongly homogeneous pattern over the muscle, while those obtained from 12×10 bipolar montage (right panel) showed such less homogeneous one (Staudenmann et al., 2005a). This homogeneity is explainable by the phenomenon of volume conduction and the related phenomenon of the presence of non-propagating far-field components (Staudenmann et al., 2005b, Stegeman et al., 1997). Consequently, the mono-polar montage is able to detect and collect muscle activities from rather the deeper active MUs than obtaining from the bi-polar one, hence the mono-polar EMG recording is expected to obtain greater force estimation by incorporating information on the deeper MUs (Staudenmann et al., 2005b, Stegeman et al., 1997).

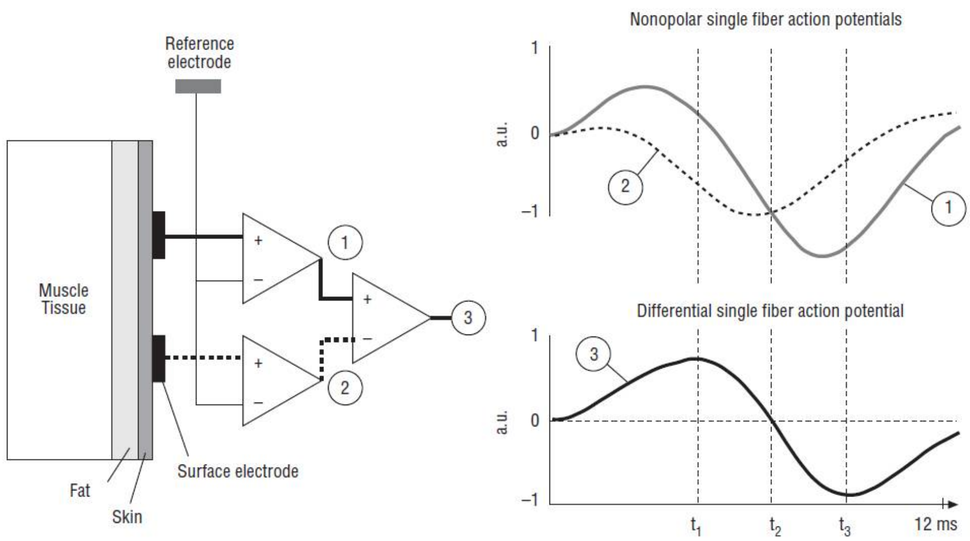


Figure 15. Conventional electrode montages shown by a schematic representation of positioning of surface electrodes. All were modified from (Garcia and Vieira, 2011).

On the other hand, EMG signals obtained from the bipolar montage, which is processed as a differentiated one, are supposed to be mainly from superficial MUs. It is a consequence of most of the common part from deeper MUs and non-propagating wave complex are largely removed by bi-polar montage. Whereby, it literally supports the other previous above found evidences, suggesting that: the bipolar electrodes need to be perfectly placed parallel to the particular muscle fibres direction being investigated. In consideration, for some non-homogeneous muscle fibres arrangement, for instant in the triceps *brachii* and many others, it is not straightforward if it is not impossible to achieve this optimal arrangement, as seen from the difference of the homogeneity pattern the among mono- and bi- polar one in figure 16.

Besides, they also evaluated a quantifying and quality of the EMG based estimation of muscle force via the Root Mean Square Difference (RMSD), for readers who are interested in more deeper details of this content, it is recommended to further study in (Staudenmann et al., 2005a). In correspondence to the previous relevant findings present above. It appeared that, the %RMSD obtained from the mono-polar montage was higher than bi-polar one, as can be demonstrated in figure 17. In addition, all these findings are also in line with the results of the research, conducted from Gabriel (Gabriel, 2011). Twenty-four college-aged male participants performed isometric contractions of elbow flexion at 40, 60, 80 and 100 percent of maximum voluntary contraction (MVC) on right arm's biceps *brachii* muscle. He discovered that, the mean spike amplitude of EMG signals obtained from the mono-polar montage was higher than the ones obtained from the bipolar, as shown in figure 18. Meanwhile, the mean spike frequency of surface EMG power spectrum, extracted from mono-polar was lower than the one obtained from the bipolar, as shown in figure 19.

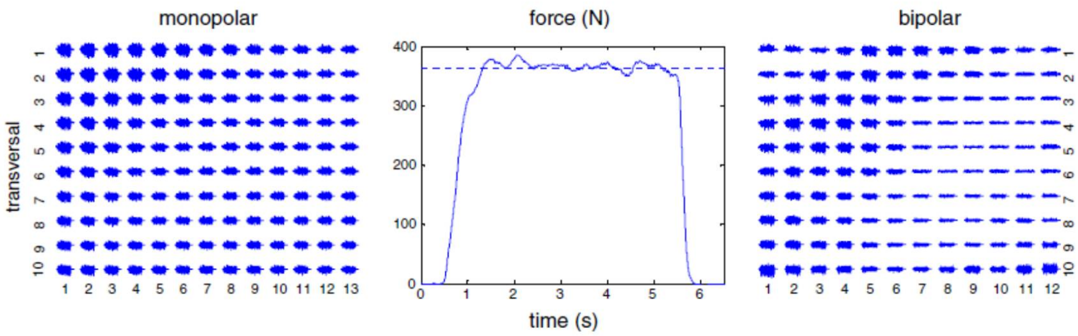


Figure 16. Force pattern and raw EMG signals were observed from two different electrode montages on the trial at 130° elbow angle and at 80% MVC, resulting in an extension force of about 370 N (Staudenmann et al., 2005a).

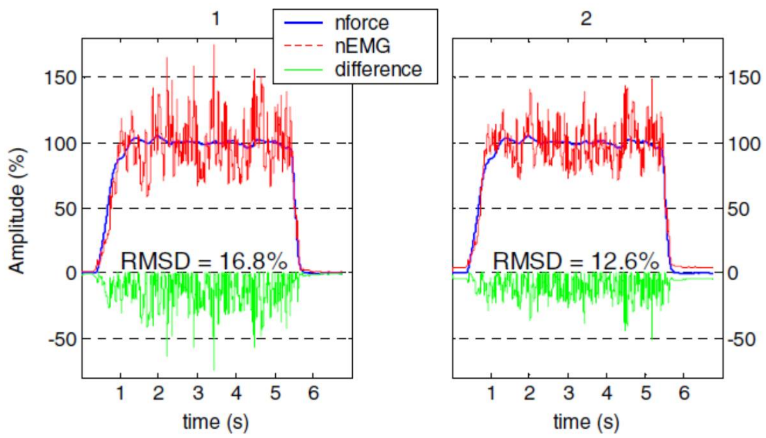


Figure 17. The force and EMG pattern of different electrode montages of one representative isometric plateau contraction (90° elbow angle at 80% MVC). Set (1) was a result from the monopolar basic and the bipolar basic for set (2). The curve below zero line indicates the negative absolute difference between both normalized signals(Staudenmann et al., 2005a).

According to all mentioned evidences above, it appears to strongly support each other pretty well over the important issue, which implies the advantage of mono-polar montage over the bi-polar one, particularly in the dynamic movement as could be described as following:

- The EMG signals obtained from monopolar montage are capable to detect deeper into active MUs than the bipolar one, which could be capable to do that just only at the superficial level of MUs.
- Only the propagating EMG signals parallel to an alignment of electrode arrays are able to be detected from the bipolar montage. No signal is able to be detected from the non-propagating one, possibly coming from the others nearby. Therefore, some non-homogeneous patterns of EMG signals were observed, which lead to the lower value of the quantifying and quality of the muscle force EMG based estimation, examining via the Root Mean Square Difference (RMSD).
- During the dynamic task, there is a huge chance of some instantly misalignment between the electrode arrays, earlier attached during the electrode placement process and the investigated MUs, underneath the skin surface. Therefore, those non-propagating wave signals would not be able to be detected properly, which could result to very low EMG signals detected, despite in reality there could be more muscle EMG activities existing by the time of examination.

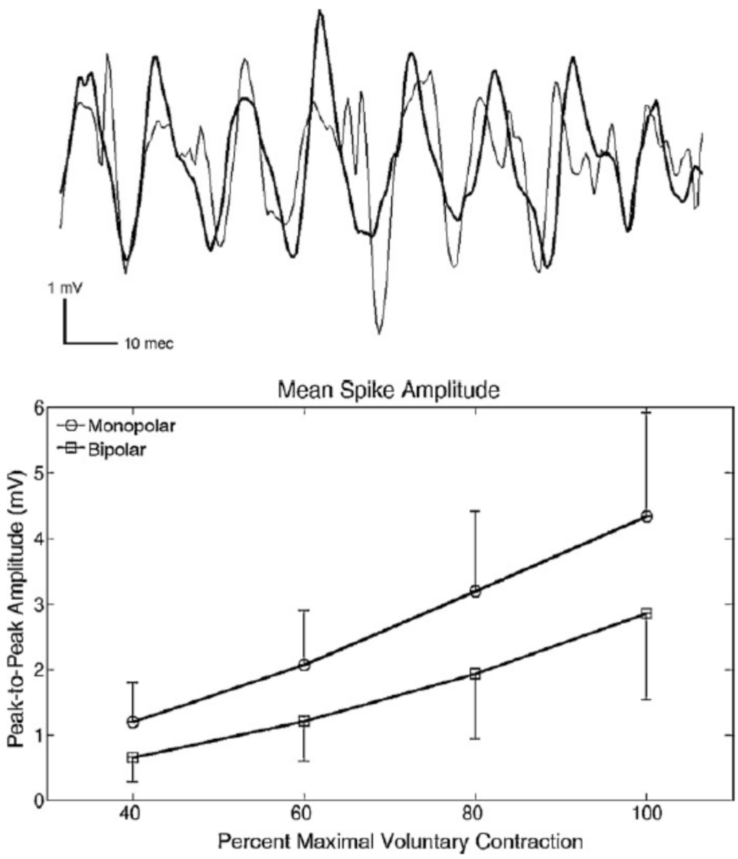


Figure 18. Left panel; representative EMG signal of mono-polar (thick line) and bi-polar (thin line), Right panel; representative Mean spike amplitude of mean and standard deviations of mono-polar (circles) and bi-polar (squares) (Gabriel, 2011).

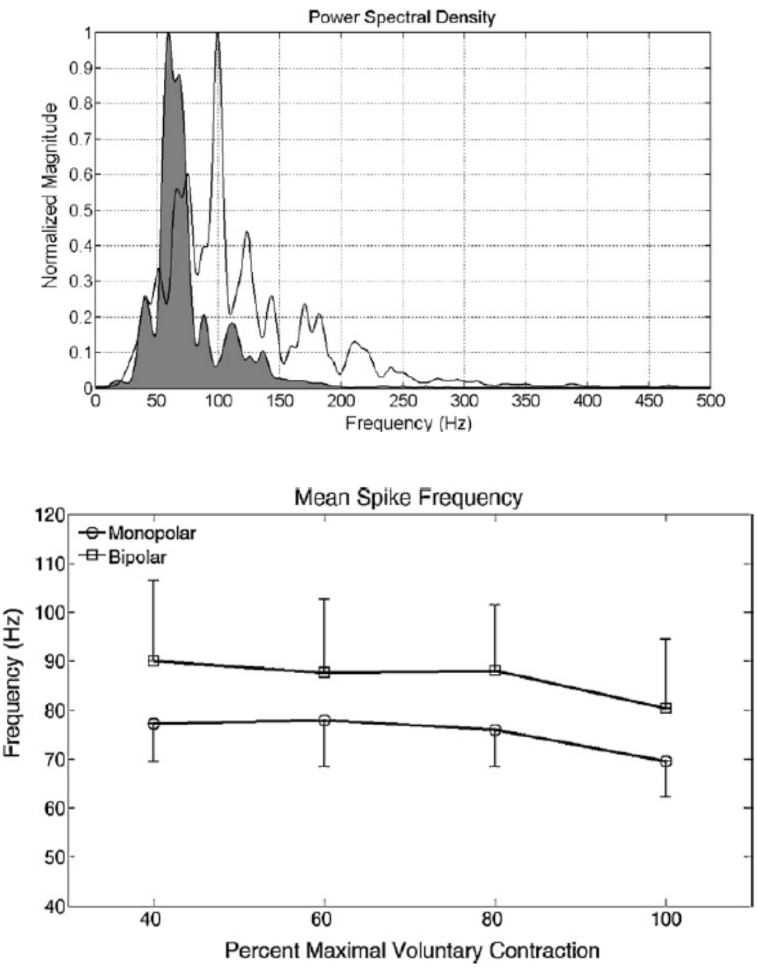


Figure 19. Top panel; representative surface EMG power spectrum from monopolar (shaded) and bipolar (un-shaded). Bottom panel; representative Mean spike frequency of mean and standard deviations of monopolar (circles) and bipolar (squares) (Gabriel, 2011) .

2.4 Signal extraction for physiological information from surface EMG

The Raw signals, recorded from surface EMG equipment, contained with essential valuable information for an estimation of muscle properties, which generally consist of muscle fatigue, muscle activation or the exertion of force or torques (Gazzoni, 2010). However, since this research study especially empathizes on the fatigue one only, then all involved parameters, which are going to be presented over this section, will be accounted for the fatigue assessment methodology only. Particularly, for all parameters that we had applied in our signal processing analysis, which were selected based on the compatible applications/functions over all involved data recording instruments, combined with the working condition/tasks of our subjects (workers). In this research, those selected parameters were roughly classified into two different categories: time-domain, and frequency-domain method, as described in details below.

2.4.1 Time-domain methods (Amplitude-related parameters)

As the information clearly stated in earlier parts: the motor units (Farina et al.) play the key role in muscle movement through its contraction, corresponding to the orders sent from the cortex of the brain via the electrical signals form (myoelectric signal). These electrical signals are subsequently transmitted from motor neuron pool, located in spinal cord, to particular muscle by motor neuron. Therefore, once muscle contraction has been made, it is then possible to observe a change of those myoelectric signals through surface EMG sensory electrodes.

The intensity of muscle contraction can be traced via an amplitude index of surface EMG, which is able to be presented in time-domain. Although, there is a slightly delay among the amplitude of surface EMG signals and muscle force, which is a result from the delay between MUAPs generation process and the muscle contraction or so called electromechanical delay (Hof, 1984, Garcia and Vieira, 2011). In the modern digital systems, there are two typical indicators of surface EMG amplitude consisting of: Average rectified value (ARV), and root-mean-square value (RMS) (Cifrek et al., 2009). Both can be defined through mathematical equations as following.

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2} \tag{1}$$

$$ARV = \frac{1}{N}\sum_{i=1}^{N}|x_i| \tag{2}$$

Where: from both equations x_i is the i^{th} sample of a signal and N is the number of samples in the epoch.

Although, the amplitude parameter either RMS or ARV is clearly capable of calculating signal amplitude well, however, there is a slightly different of the result among the two, which is due to the different mathematic operator (square root). Both are widely selected for amplitude estimation arbitrarily, but RMS might be more preferred over the ARV, as it posits a physical meaning (Garcia and Vieira, 2011). By this selectable option, combined with the more preferable number of utilization, therefore in this research RMS was selected to be our amplitude analysis over time-domain method.

In general, the amplitude-related parameters are considered less discriminative, with respect to the frequency-related parameters (see section 2.4.2). This could be interpreted that, its results are seemingly with pretty high variability within the considered group and low contrast value between the comparative groups, which is probably caused by the higher inter-subject variability (Laura A.C. et al., 2006). This occurred regarding to the physiological phenomena, as well as the detection system and the geometrical distance between muscle fibres and skin, with these, it does result to a strong impact to the inter-subject variability (Farina et al., 2002a, Farina et al., 2002b, Laura A.C. et al., 2006).

In responding to that variability, the normalized RMS value was selected to be an analysed amplitude-related parameter in this research, on the purpose of minimizing as much variability as possible. By this, all computed RMS values during the task will be normalized by the value from subject's reference RMS, obtained from the standard isometric test contraction over the duration of 30s (Suurkula J. and Hagg G.M., 1987), which was performed at the beginning of the workday, just before starting of the tasks. The normalized RMS signal of dynamic task performing can be shown as in figure 20.

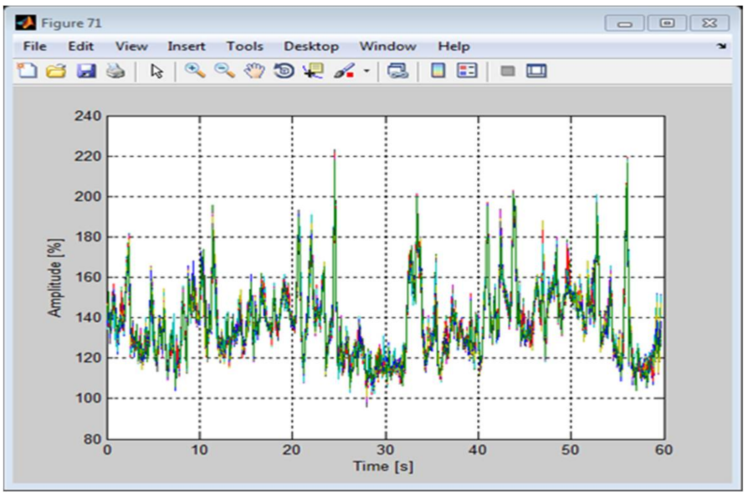


Figure 20. Normalized RMS value at some certain 60s of recorded period

2.4.2 Frequency domain methods (Frequency-related parameters)

As a mathematic standpoint saying: any signal represents a combination of many sinusoid waveforms and while time domain can demonstrate a tendency of signal change over time, however on the other hand, the frequency domain comes with the ability of demonstrating the distribution of all involving power frequency spectral, which consist of the fundamental frequency and other remaining different harmonics. All of those power frequency spectrum generally has a boundary across the band pass filter length, that normally is set between 10 – 500 Hz, which is considered as much suitable for surface EMG (SENIAM). Some of a simple example of the power frequency spectral distribution can be representatively demonstrated in figure 21.

Not so relatively long time ago, there was a mathematical tool introduced that capable to transform time domain into frequency domain. It was introduced by France mathematician named Jean-Baptiste Joseph Fourier (21 March 1768 – 16 May 1830). The methodology was later called the Fourier transform procedure of his honour. In addition, this procedure is also capable of transforming the frequency domain back to domain, which can be accomplished by the inverse Fourier transform. More interestingly, the spectrum of all frequency components, representing the frequency domain, are involved with the fatigue development manifestation, which can be utilized in this research study.

In general, there are two frequency spectral parameters, commonly used in surface EMG fatigue manifestation. They are called mean frequency (MNF) and median frequency (MDF) (Hof, 1991, Garcia and Vieira, 2011, Merletti et al., 2001). Both parameters are responsible to represent the central tendency of the power frequency spectrum, but with a different definition as could be described as following: the mean frequency (MNF) is defined as the centre of gravity line of power spectral frequency, meanwhile median frequency (MDF) represents the splitting point of two equal power spectrum (Roberto Merletti and Parker, 2004), as shown each definitions graphically in figure 22.

By the way, as mentioned previously on section 2.2.2 (Myoelectric manifestation of fatigue) saying that: once an increase of lactate concentration occurs, as a result of the decrease of an intracellular pH changes during muscle fatigue, this phenomenon contributes to MUAPs propagation and shape change (Cifrek et al., 2009, Garcia and Vieira, 2011). This has an influence to the decrease of muscle fibre conduction velocity (CV), which plays an important role in influencing the power spectrum frequency that tends to be compressed and shifted toward the lower frequency boundaries. Therefore, it is possible and most likely preferable to determine the fatigue development by considering the direction of the power frequency spectrum compression. By this principle, two indicators will be utilized, consisting the mean spectral frequency (MNF) and median spectral frequency (MDF). They will be observed the shifting toward lower frequency direction during the progress of fatigue development, as representatively demonstrated in figure 23 and figure 24 respectively.

It is obvious that, the conduction velocity (CV) and frequency-related parameters, both have a direct relation to each other, namely once the conduction velocity (CV) decrease/increase, the frequency-related parameter values will decrease/increase as well. And since this research study mainly focused on muscle fatigue development in real world working task and condition, with nonideally controllable movements, unlike the ones mostly set up in the laboratory. The mono-polar montage was then selected for this study, in response to obtain as most efficient detected EMG signal as possible, as well as the most original/deeper EMG raw signals from MUAP as previously described on section 2.3.3.2 (Electrode montage recording configuration). Therefore, conduction velocity (CV) parameter, which relies on the differential MUAP waveform was impossible to be calculated correctly, due to this technique is only efficient for a differential mode of bi-polar montage.

By the way, for both mean spectral power frequency (MNF) and median spectral power frequency (MDF) parameters, they can be explained in term of mathematical equation as following:

MDF: splits the spectrum into two parts of equal power

$$f_m = \frac{\int_0^\infty fP(f)df}{\int_0^\infty P(f)df} \tag{3}$$

MNF: Centre of gravity line

$$\int_0^{f_{med}} P(f)df = \int_{f_{med}}^\infty P(f)df = \frac{1}{2}\int_0^\infty P(f)df \tag{4}$$

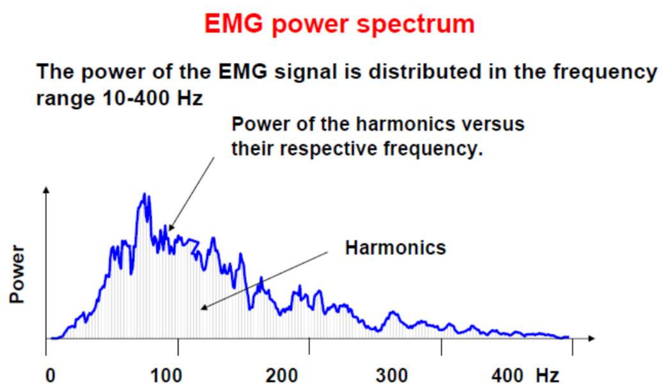


Figure 21. Representative graphics of power frequency spectrum banded pass filter with frequency range 10-400 Hz (Roberto Merletti and Parker, 2004).

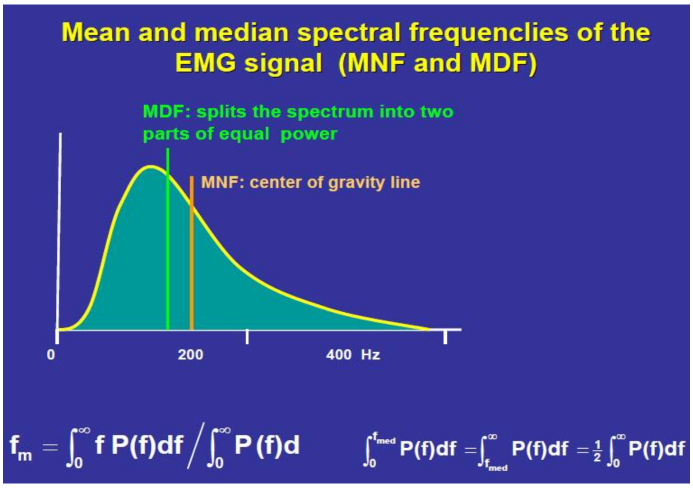


Figure 22. Representative graphics of power frequency spectrum and its definitions of mean spectral frequency (MNF) and median spectral frequency (MDF) (Roberto Merletti and Parker, 2004)

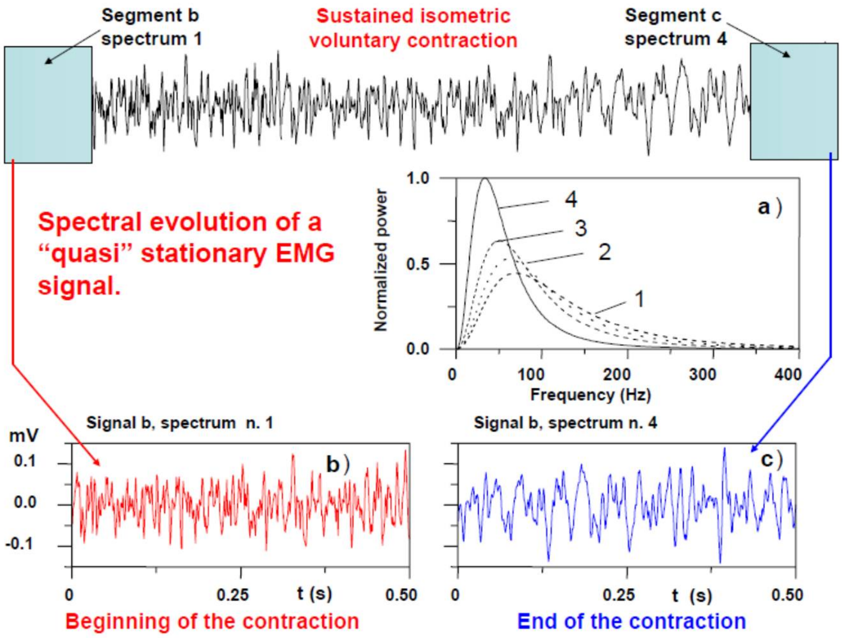


Figure 23. The demonstration of EMG signal waveform over time as fatigue developed and its differently compressing power frequency spectrum shape (Roberto Merletti and Parker, 2004).

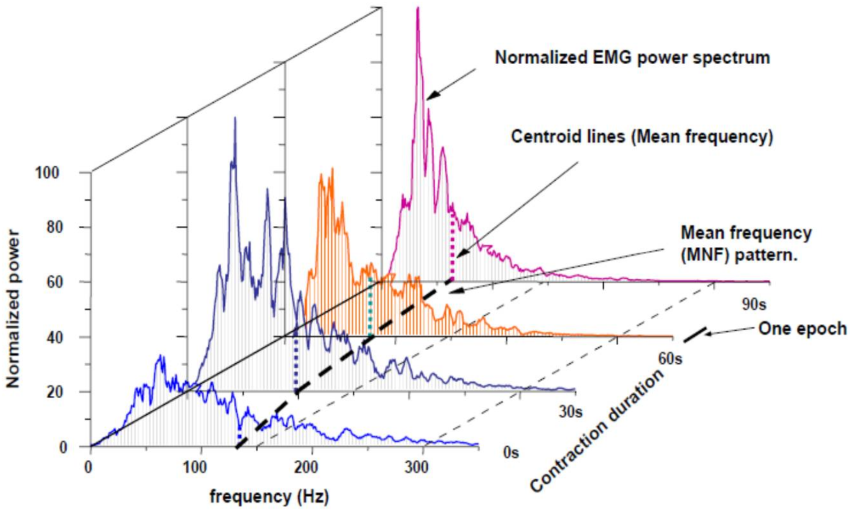


Figure 24. The demonstration of the power frequency spectrum compresses toward lower frequency as muscle fatigue developed, demonstrated via its centroid line (MNF) shifting direction (Roberto Merletti and Parker, 2004).

2.5 Musculoskeletal disorders (MSDs) and Muscle fatigue.

In general, an individual always performs moving activities every day in daily life, ranging whether from the basic ones such as: walking, sitting, running till the more complex ones like sport, working etc. By this fact, it is obviously showing that, musculoskeletal system plays an important role in these essential activities.

Musculoskeletal system is a very essential system, its function contributes to any movement of our body whether for a single or some parts or even for the whole body movement. It is a complex entity, consisting of bones, joints, muscles, tendons, ligaments, bursa, nerves and blood vessels. Being physically active is beneficial for our musculoskeletal system, however an overload of physical strenuous muscle tasks may cause potential threats against its healthiness. Regarding to awkward postures, repetitive work or heavily manual materials handling may lead to damaging of such system.

Musculoskeletal disorders (MSDs) are caused when: physical capacity of the muscles, joints, ligaments and so on, are not in balance with external forces, acting upon the body. Musculoskeletal disorders (MSDs) are the most common work-related health problem in Europe, affecting millions of workers. Across the EU27, various kind of work related MSDs symptoms were involved, including backache, which accounts 25% of workers, along with 23% report muscular pains (OSHA_European, 2007). MSDs became the most major cause of work-related absence in practically all EU27 Member States, reducing companies' profitability and also affected the social costs of governments. With this impact, it could potentially result in up to 40% of workers' compensation in some EU27 states, which could cost as high as 1.6% of those countries' gross domestic production (GDP) (OSHA_European, 2007).

Most of work-related MSDs are cumulative disorders, resulting from repeated exposure to high- or low-intensity loads over a long period of time. The symptoms may vary from discomfort and pain to decreased body function and invalidity (OSHA_European, 2007). MSDs, or musculoskeletal disorders, are injuries and disorders of the soft tissues (muscles, tendons, ligaments, joints, and cartilage) and nervous system. They can affect nearly all tissues, including the nerves and tendon sheaths, and most frequently involve the arms and back (OSHA_U.S., 2000(Revised)).

These painful and oftentimes disabling injuries generally develop gradually over weeks, months, and years. Most of the first indication of this symptom is fatigue over muscles, often exposed to the involved muscle load. Muscle fatigue is usually caused by repetitive or sustained work, short work cycles, and localized muscle loadings, and being under muscle fatigue results in declination of force, generated by muscle itself (Troiano et al., 2008). As already mentioned earlier that muscle fatigue is developed as a result of a chain of metabolic, structural and energetic changes in muscle due to an insufficient oxygen and nutritive substances, supplied through blood circulation, as well as a result of changes in the efficiency of the nervous system (Cifrek et al., 2009).

In summary, once muscle fatigue caused by sustained or repetitive movement or whatever occurs on particular muscles over a long period of time, this will be developing into pain/injuries phenomenon in the next step. Subsequently, if this situation is still continuously going on, it could eventually lead to MSDs at last, as demonstrated its major development in the chart in figure 25.

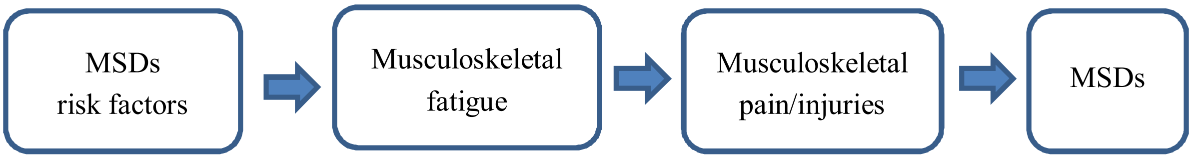


Figure 25. The major development of MSDs over time

2.5.1 Work-related MSDs risk factors

In this section and all of this study, it was emphasized on only work-related MSDs context. It is very important to know, what the causes behind this issue are, in order to take the right actions against them in advance. There are four major risk factors that may potentially contribute to work-related MSDs. All can be described according to the report of the European Agency for Safety and Health at work (Abbiss and Laursen, 2005) as following:

- Physical or biomechanical work-related factors
- Organizational or psychosocial work-related factors
- Individual or personal factors
- Social-related content factors

1) Physical factors

Physical factors are the most significant contributor of work-related MSDs issue. It involves in many points, for example, work procedures, equipment and environment. These potentially contribute to biomechanical stress in musculoskeletal system (muscles, tendons, spinal discs and nerves), which is a key factor, leading to MSDs cause at last. As much imaginable working scenario as it could be, there are many physical risk factors as possibly described as following:

- Excessive force:
  Applying an excessive force repeatedly is responsible to muscle excessive contraction, which accelerate to muscle fatigue phenomenon.
- Repetitive:
  Using the same musculoskeletal system over a certain long period of time is mainly responsible to fatigue, which is the major initial indication of MSDs.
- Awkward postures:

For example repeatedly using the hands above shoulder height or with the wrists noticeably bent.

- Vibration:
  For example the use of chainsaws, hammer drills etc. The vibration causes potential blood circulation disruption in fingers, nerves of the hand and arm.
- Static postures:
  For example often occurring in some professions such as: dentists, computer operators, hairdressers etc. Their occupations require repeatedly long-term static postures, such as shoulder muscles, arms, which are maintained steadily for the particular work characteristics.
- Prolonged standing :
  This may result in occurring of fatigue and discomfort in legs, which can potentially contribute to MSDs on the legs
- Prolonged sitting:
  This requires prolonged relevant muscle contraction to hold the body trunk, neck and shoulders in a fixed position. By this, it contributes to the disruption of blood vessels circulation, which lead to muscle fatigue/injuries and eventually MSDs at last.
- Manual handling:
  Particularly in repetitive heavily manual handling, and it will be even more severe, if combined with an awkward work postures.
- Cold environments:
  Coldness will lead to the inefficiency of blood vessels circulation, and may eventually cause vascular and neurological system damage. This does affect the musculoskeletal system. Moreover, it is most likely that, workers with cold hands may exert more force than necessaries, affecting muscles, soft tissues and joints. By these, it can potentially lead to more rapid fatigue, and soon the development of disorders.

2) Organizational and Psychosocial factors

The poor organization provided from an employer, such as a long-term intense level exposure of physical risk factor, which can eventually result in MSDs as described on the above section. This problematic cause can be settled by the well organization management provided by either employer or even from the employees themselves, such as:

- Avoid the exposure to MSDs risk factors.
- Applying protective measures combined with PPE (Personal Protective Equipment) on unavoidable work types containing with MSDs risk factors.
- Establishing prevention and control measures against MSDs risk factors, particularly at the sources of such risk.
- Work station circulation of workers in the production line.
- Providing interrupting short break or exercise amid a prolonged working period.
- Better ergonomics work station design.

- Reducing repetitive heavily manual handling by increasing the autonomous machine procedure replacing those manual handlings.
- Providing training and information to workers for a better properly knowledge skill, in term of for example: working methods, proper performing posture, movement and technique. In an attempt to increase working skill that is important for safer working performing.

In addition, psychological factors are also crucially corresponding with this issue. Regarding to mental strain is capable to cause muscular tension, and increase an existing physical strain. Work condition that may cause mental strain can be roughly explained as following:

- A tight dead line or schedules.
- An insufficient rest or recovery time.
- Work pressure and mental demand.
- Lacking of good governance from employer

3) Individual factors

Individual factors are considered as non-work risk factors. Each individual has its own different factors, which significantly result in a different impacts on MSDs. Physical capacity, age, prior medical history, or event smoking habit are very responsible to the contribution in MSDs. Individual non-occupational factors such as obesity, pregnancy, rheumatoid arthritis, acute trauma and endocrinological disorders may also affect the occupational MSDs.

4) Social context factors

Social context factors are also non-work risk factors, which have potential to cause or may increase susceptibility to MSDs. Social context factors for example: some type of sport, leisure activity and housekeeping work at home, these may increase or even cause a risk of MSDs development, particularly when it is combined with other MSDs risk factors, whether physical, organizational and psychosocial or individual factors.

2.5.2 MSDs syndrome

According to the report of the European Agency for Safety and Health at work (Abbiss and Laursen, 2005), MSDs is obviously one of the most complex disorders. Some MSDs appear with clear clinical features, but some MSDs appear without evidence of clear specific disorders. Many MSDs cases are transient and episodic, due to the pain often disappears after rest or changed activities, or even disappears for a while then recur a few month or years later. On the other hand, some present persistent or irreversible set of symptoms, regarding to different conditions such as tissue types, acting force level etc. Therefore most physicians and researchers classify MSDs either as specific or non-specific disorders.

Some MSDs are **specific,** in this way, they have clear clinical features, which include lumbosacral radicular syndrome in the low back, carpal tunnel syndrome in the wrist, and patellar tendonitis in the low extremities. Some MSDs are **non-specific,** in this way, pain is present without evidence of a clear specific disorder. One in every three patients who present in primary health care experience pain in the absence of a clear specific disorder. Certainly, this does not mean, these symptoms are trivial or non-existent.

3 REVIEW OF LITERATURE

This section was designed to demonstrate the recently up to date application of high-density surface EMG in muscle fatigue evaluation. The presentation was going to be organized in the term of publications that author and research team had accomplished consecutively, since the start of the Ph.D. research development stage till the time of this thesis report being written.

There were 3 publications having been conducted over the period. All three articles were carried out to comprehensively investigate the application of high-density surface EMG and muscle fatigue evaluation following the PRISMA statement, specifically for reporting systematic reviews and meta-analyses of studies. Therefore, this section will reveal the most up to date scientific found evidences related to the topic of this thesis. Moreover, it would be able to serve some supporting information for proving/answering this research hypothesis as well. They could be demonstrated subsequently according to the time of publication as following.

Publication I (High-Density Surface Electromyography Applications & Reliability vs. Muscle Fatigue – A Short Review)

T. Sa-ngiamsak, J. Castela Torres Costa, J. Santos Baptista. 2014. High-Density Surface Electromyography Applications & Reliability vs. Muscle Fatigue – A Short Review. Occupational Safety and Hygiene II. Taylor & Francis Group, London. 265-269

Publication II (The Applications of muscle fatigue/Muscle activity assessment using Multi-channel surface EMG during repetitive movement – A Short review)

T. Sa-ngiamsak, J. Castela Torres Costa, J. Santos Baptista. 2015. The Applications of muscle fatigue/Muscle activity assessment using Multi-channel surface EMG during repetitive movement – A Short review. Occupational Safety and Hygiene III. Taylor & Francis Group, London. 143-148

Publication III (Multi-channel Surface EMG for Muscle fatigue/activity evaluation in Ergonomics: A Systematic Review)

T. Sa-ngiamsak, J. Castela Torres Costa, J. Santos Baptista, C. Vila-Chã. Multi-channel Surface EMG for Muscle fatigue/activity evaluation in Ergonomics: A Systematic Review. Accepted to be published from DYNA Journal (Waiting for publication process).

Publication I (Occupational Safety and Hygiene II. Taylor & Francis Group, London. 265-269)

High-Density Surface Electromyography Applications & Reliability vs. Muscle Fatigue – A Short Review

T. Sa-ngiamsak, J. Castela Torres Costa, J. Santos Baptista

Research Laboratory on Prevention of Occupational and Environmental Risks (PROA/LABIOMEP), University of Porto, Portugal

ABSTRACT: Muscle fatigue has been documented in various occupations. The aim of this study was to evaluate the applications of high density surface electromyography (HD-sEMG), in context of its variables/factors correlating with muscle fatigue, beside with its feasibility and reliability in muscle fatigue assessment. The search was performed over 33 electronic databases through integrated and metasearch search methods. Seven studies were included in the review. Four of them associated with HD-sEMG applications in muscle fatigue assessment and three other studies involving with reliability in muscle fatigue assessment. Evaluation by HD-sEMG is feasible and reliable in muscle fatigue assessment. There are many variables/factors correlated with muscle fatigue. Its reliability in terms of repetition and reproducibility of a diagnosis were also proved. This review indicates that applications of HD-sEMG are feasible and reliable in order to assess muscle fatigue whether static or dynamic contraction.

1. INTRODUCTION

Muscle fatigue has been documented in different occupations (Troiano et al., 2008). Muscle fatigue results in the declination of force generate by the muscle. It can be caused by repetitive or sustained work, short work cycles, and localized muscle loadings (Troiano et al., 2008). Muscle fatigue is developed as result of a chain of metabolic, structural and energetic changes in the muscle, due to the insufficient oxygen and nutritive substances supplied through blood circulation, as well as a result of changes in the nervous system efficiency (Cifrek et al., 2009).

Intramuscular electromyography signal recording so-called invasive technique was first introduced by Adrian and Bronk in 1929 (Henneberg, 2000). It is necessary to use the insertion of needles into the muscle and it has become a classic tool to investigate individual motor properties, particularly in clinical examination. This use is due to an important feature of the needles, type electrode that by limiting the diffusion effect can detect electrical potentials near the active muscle fibres in term of conductive capacity (Merletti et al., 2008). However in some cases the use of needles insertion is not either desirable or comfortable, such as in the children clinical examination, sport or ergonomics (Merletti et al., 2008). Surface electromyography (sEMG) is a non-invasive technique that can be used as an alternative to such limitation, although its properties couldn’t be replaceable to the invasive technique in clinical ex-amination (Merletti et al., 2008). Surface EMG is widely used to measure muscle action potentials, through the placement of surface electrodes on the skin overlying a muscle or group of muscles (Drost et al., 2006). The basic sEMG configuration has a single channel, that can only provide the examining information only over the small area of muscle, and it is still unable to investigate the spatial distribution of muscle activity, as well as the application of intramuscular technique (Madeleine et al., 2006). In the last decade, the evolution of sEMG technology has been developing rapidly. The new technique of two-dimensional array systems, so-called high-density surface electromyography (HD-sEMG) was presented and has been increasingly applied in this study area. This technique provides the possibility to investigate the spatial distribution of single muscle activity, moreover it also allows the visual investigation through the topographical mapping of muscle activity (Madeleine et al., 2006). Nevertheless there are some questionable outcomes of such HD-sEMG applications and their reliability. Can they actually be used as a major tool in an attempt to investigate muscle fatigue?

This work was conducted to present the current situation of HD-sEMG applications, in context of its variables/factors correlating with muscle fatigue, be-side with its feasibility and reliability in muscle fatigue assessment. The objective focuses on getting an actual vision, clear and comprehensive of the applications and reliability of HD-SEMG.

2. METHODS

2.1 Search strategy

The literature search was conducted on March 29, 2013 and April 8, 2013. The search was performed over 33 electronic databases through integrated and metasearch search methods. The database type was E-journals. The key search terms focus on words such as “surface EMG”, “fatigue”, “musculoskeletal disorders”, “muscle”, “ergonomics” and were used in all the database with the appropriate Boolean operators (such as And and Or). In addition another literature searches were also performed through the google search engine and reference list of those relevant articles. Only full papers were considered and insufficient information formats, such as abstracts published in term of conference or workshop proceedings were not included.

2.2 Screening and Eligibility criteria

After duplication removal, all the articles found were considered as excluded after being screened following these criteria:

- No related subject
- Publication before 01-01-2005
- Language not accessible
- Text not available.

Articles were considered eligible if they meet the following criteria:

- Studies which whose objectives are involved with HD-sEMG
- Studies which testify the effectiveness, application or reliability of HD-sEMG assessment
- Studies which provide the information about sEMG based muscle fatigue evaluation in biomechanics
- All the above considered studies are performed in humans but not in animals.

3. RESULTS

3.1 Study selection

The details of the selection of all relevant articles both, excluded articles and included articles were performed through several criteria, based on the PRISMA statement for reporting systematic reviews and meta-analyses of studies (PLoS_Medicine, 2009). All those details can be shown in Figure 1.

3.2 HD-sEMG applications in muscle fatigue assessment

Four of the seven included studies examined muscle fatigue by using HD-sEMG (table 1). Two of them were conducted with static contraction, one study was conducted with dynamic contraction, and another one with both static and dynamic contraction. All of these studies were assessed on Biceps brachii, upper trapezius and lumbar muscle.

The first study from table 1. (Troiano et al., 2008), Amedeo Troiano and his team conducted the experiment to assess fatigue in isometric contractions of the upper trapezius muscle. The results presented an EMG surface amplitude increased during the con-traction meanwhile mean frequency of the power spectrum (MNF), fractal dimension (FD), and muscle fibre conduction velocity (CV) decreased, and this provided indications of fatigue and could be predictive of endurance time (ET).

The second study from table 1 (Falla and Farina, 2005), Deborah Falla and Dario Farina presented an experiment to compare average muscle fibre conduction velocity (CV) be-tween patients with chronic neck pain and an healthy control group during dynamic contraction. It appeared that CV was decreased by fatigue during dynamic contraction, but CV of the upper trapezius muscle was higher in people with chronic neck pain than in the control group. It was concluded that, this may be associated with the histological and morphological changes which had previously been identified in people with pain over the trapezius muscle.

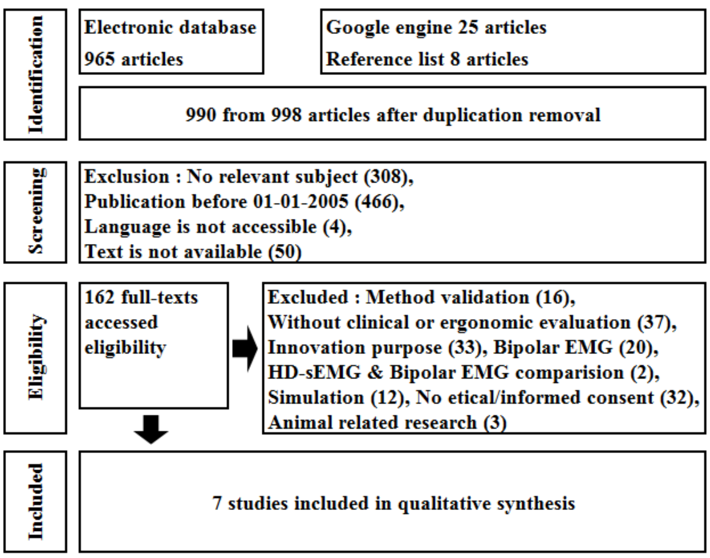


Figure 1. Selection criteria of the relevant articles.

The third study from table 1 (Kallenberg and Hermens, 2009), performed an experiment to assess motor properties between a chronic stroke patients group and healthy control group, by using High-Density Surface EMG during both dynamic and static con-traction. For dynamic contraction larger motor unit action potentials (MUAPs) reflected in a higher value of the root mean square of motor unit action potentials (RMSMUAP) were found in stoke group when compared with the control group. Furthermore there was a correlation between a clinical scale, the Fugl-Meyer score (Physical performance assessment tool), and the ratio of RMSMUAP at the affected side divided by unaffected one.

In the fourth study of table 1 (Hu et al., 2007), Yong Hu and his team performed an experiment by using the sEMG topography pattern identified Low Back Pain (LBP) rehabilitation. They found that in all healthy subjects in the control group, sEMG topography patterns presented symmetric muscle activities. Meanwhile sEMG topography patterns obtained from 5 LBP patients group presented obviously asymmetric and different from the normal pattern. This was able to conclude that sEMG topography illustrates the distribution of muscle activities, which provides a visible result of lumbar muscle coordination.

Table 1. HD-sEMG applications in muscle fatigue assessment.

Authors	Year	Country	Number of	Number of Electrodes	Contraction Subjects	Muscle types
Amedeo Troiano et al.	2008	Italy	64	14	Static	Upper trapezius
Deborah Falla & Dario Farina	2005	Australia	4	19 patients 9 controls	Dynamic	Upper trapezius
L.A.C Kallenberg & H.J. Hermens	2009	The Netherlands	16	18 patients 20 controls	Static& Dynamic	Biceps *brachii*
Yong Hu et al	2007	Hong Kong	20	5 patients 30 controls	Static	Lumbar

3.3 HD-sEMG reliability in muscle fatigue assessment

The other three of the seven included studies dealt with reliability in muscle fatigue assessment. Their details are presented in table 2. There were three different methodologies performed to assess reliability of HD-sEMG applications in muscle fatigue assessment.

The first study from table 2 (Kim et al., 2007), GyuTau Kim and his team performed an experiment to assess reliability of muscle fatigue indices correlation. Measurements were done by surface EMG and compared with intramuscular EMG or invasive technique. It appeared that muscle fatigue indicts including with root mean square (RMS), average rectified value (ARV) and mean frequency of the power spectrum (MNF) typically changed in accordance with the results obtained from intramuscular EMG or invasive technique. It appeared that MNF decreased meanwhile RMS and ARV increased as muscular fatigue progressed. A linear correlation was also observed and it was concluded that the change rates in RMS and ARV values, of intramuscular EMG are almost the same rate as surface EMG.

In the second study presented in table 2 (Barbero et al., 2011) Marco Barbero and his team performed the experiment to assess reliability of HD-sEMG applications by evaluating intra-rater and inter-rater reliability and the suitability of surface EMG. It appeared that both intra-rater and inter-rater reliability analysis showed an almost perfect agreement. This study provided strong evidence that visual estimation of innervation zone location is a reliable procedure.

The third study from table 2 (Kallenberg et al., 2009), Laura A.C. Kallenberg and her team performed an experiment to assess the within-day and between-days reproducibility of variables obtained from linear array sEMG during three functional tasks: a shoulder abduction, ironing and head turn task. The ICC (Intra-class correlation coefficients) value for investigation of EMG variables were higher than 0.7 during the three tasks, meanwhile ICC values > 0.6 are commonly accepted as a good reliability. This high reliability level implies that, they could be used to distinguish between-subjects, what may prove to be important for clinical practice.

Table 2. HD-sEMG reliability in muscle fatigue assessment.

Authors	Year	Country	Number of Electrodes	Number of Subjects	Comparative reliability	Muscle types
GyuTau kim et al.	2007	USA	N/A	5	Intramuscular	Rectus femoris
Marco Barbero et al.	2011	UK	64	10	Inter & Intra-rater	Upper trapezius
Laura A.C. Kallenberg et al.	2009	The Netherlands	8	12	Reproducibility	Upper trapezius Sternocleidomastoid

4. DISCUSSION

From the seven included studies, four were found associated with the applications of HD-sEMG, and three of them were found to be associated with the reliability of HD-sEMG assessment in muscle fatigue.

For the applications of HD-sEMG both static and dynamic contraction demonstrated that, there are many variables/factors correlated with muscle fatigue. Namely during the contraction surface EMG amplitude will be increased, meanwhile MNF, FD and CV decreased. This provides the sign of fatigue and could be productive of ET (Troiano et al., 2008). While surface EMG amplitude increased during the contraction as fatigue progressed, it also caused the root mean square (RMS) value of motor unit action potential (MUAP) to be increased as well. This fact was remarkably related with one study that com-pared the RMS value of motor unit action potential (MUAP) between healthy people (Control group) and the stroke group. As the result, it was perceived that RMS of stroke group was higher than the one which obtained from healthy group. This implies that the muscle activity in stoke group is higher than the healthy group (Kallenberg and Hermens, 2009).

In addition the comparison between healthy people (Control group) and patients group with chronic neck pain during the dynamic contraction of one study, demonstrated that the CV of the upper trapezius muscle was higher in people with chronic neck pain than in the control group. It was concluded that, this may be associated with the histological and morphological changes which had previously been identified in people with pain over the trapezius muscle (Falla and Farina, 2005). Moreover another study was performed by using the sEMG topography pattern to identify LBP rehabilitation, Its result showed that, sEMG topography patterns obtained from the LBP patients group presented obvious asymmetry and different from normal pattern. This leads to the conclusion that sEMG topography illustrates the distribution of muscular activities, which provides a visible result of lumbar muscle coordination (Hu et al., 2007)

For the reliability of HD-sEMG assessment, three from the seven included studies were found with three different systematic comparative methodologies. All of those assessments had demonstrated the reliability of HD-sEMG applications. One study suggested the reliability of fatigue indices measured by surface EMG compared with intramuscular EMG or invasive technique. It appeared that muscle fatigue indices obtained from surface EMG including RMS, ARV and MNF typically changed in accordance with the results obtained from intramuscular EMG or invasive technique, namely MNF decreased as muscle fatigue progressed and particularly RMS and AVR increased almost at the same rate obtained from the intramuscular EMG or invasive technique. This implies that the results of surface EMG are in accordance with the intramuscular EMG or invasive technique, which is generally used in clinical diagnosis (Kim et al., 2007).

Another two studies proved the reliability of HD-sEMG applications in terms of visual estimation of the EMG signal and reproducibility of variables obtained from HD-sEMG. They were performed through different evaluation methods, the intra-rater and inter-rater reliability methods and the reproducibility method. These methodologies presented a high reliability in the applications of high density surface EMG, according to both intra-rater and inter-rater reliability analysis, indicating an almost perfect agreement (Barbero et al., 2011). And for the ICC indicator in reproducibility analysis, it presented a score higher than 0.7 which is considered acceptable as a good reliability (Kallenberg et al., 2009). These evidences implied that the applications of HD-sEMG are reliable in statistics, in term of multiple repetition of diagnosis. Namely the visual estimation of EMG signal over innervation zone and reproducibility of variables/factors obtained from HD-sEMG recordings are a reliable procedure.

5. CONCLUSION

The result of this review indicates that, the applications of HD-sEMG are feasible and reliable in order to assess muscle fatigue. The results of the various studies lead to the conclusion that there are many variables/factors correlated with muscle fatigue and also accordant with intramuscular EMG or invasive technique either static or dynamic contraction. And its reliability in term of multiple repetition of diagnosis and reproducibility was also proved. In addition its remarkable applications to evaluate muscle activity through the sEMG topography pattern over particular muscle, might show some musculoskeletal disorders (MSDs) and symptoms. From all these evidences have revealed that HD-sEMG is increasingly more useful in applying as a muscle fatigue investigation tool.

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The Applications of muscle fatigue/Muscle activity assessment using Multi-channel surface EMG during repetitive movement – A Short review

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ABSTRACT: Repetitive movement is commonly observed in daily-life activities. Exposure to it for a long period of time can cause muscle fatigue. The aim of this study was to examine and present the applications of muscle fatigue/muscle activity assessment during the repetitive movement by using multi-channel surface EMG. The systematic searches were conducted over 35 electronic databases, through the search methods type of integrated and metasearch. Four studies were included in the review. Two of them were associated with one-dimensional array surface EMG, and another two studies were involved with two-dimensional array surface EMG. Both types and their utilization of advanced mathematic algorithm were capable to evaluate EMG signal during dynamic tasks. In order to have the higher accuracy and reliable results, the two-dimensional array surface EMG is required, due to its multiple detection sites can provide greater information detected over larger muscle fibre area.

1. INTRODUCTION

Repetitive movement is commonly seen in daily-life activities, for instance in sport particularly widely seen in the occupational task, such as existence in the production line of industrial sector, where workers have to perform their work tasks repetitively roughly 8 hrs a day, 5-6 days a week and for many years during their employment. Repetitive movement over such a long period of time can result in muscle fatigue that is a consequence from a chain of metabolic, structural and energetic change in muscle, due to the insufficient oxygen and nutritive substance supplied through blood circulation, as well as a result of change in the nervous system efficiency (Cifrek et al., 2009). Most of the studies investigating muscle fatigue/muscle activity have been limited to either isometric contractions of increasing force or sustained isometric contractions (A and K, 2006, BU et al., 2000). That is not functional in most of the applied fields, such as occupational health and safety, sport etc. The main obstacles of this limitation consist of, firstly due to the artefacts generated from the movement and vibration on the fixed dry inter-electrode closely located over the skin of subject during the dynamic contraction. Secondly due to the non-uniformity of motor unit distribution that changes rapidly over time of repetitive movement, depending on the different location within the muscle (Falla et al., 2006). So far there have been a number of studies conducting to investigate muscle fatigue/muscle activity by using a classic bipolar electromyography (EMG) applied over a tiny area of muscle region. And due to the complexity of surface EMG signal extraction then leading to only simple tasks are frequently considered (D et al., 2004). Preferably isometric or constant force contraction has been used to assess muscle property through EMG signal for over three decade (B et al., 1981, L et al., 1989). This poor functional property can provide such limited information, of frequency content necessary for myoelectric fatigue manifestations assessment, and for its EMG signal amplitude, that can be used to evaluate muscle activation through motor unit distribution. Moreover as a result from its very small detected area over the small portion of muscle, this also leads to a high variance of the EMG variables, and may even be contradictory (Falla et al., 2014). This review was conducted to examine and present the applications of muscle fatigue/muscle activity assessment during the repetitive movement by using the multi-channel surface EMG considered as a more suitable tool than using just a pair of bipolar EMG, in order to obtain a comprehensive insight over its current situation of muscle fatigue/muscle activity during the repetitive movement.

2. METHODS

2.1 Search strategy

The literature searches were conducted on August 28, 2014, August 31, 2014, September 1, 2014 and September 5, 2014. The searches were performed over 35 electronic databases through the search method of integrated and metasearch. The database type was E-journals. The key search terms were focused on words including “Multi-channel surface EMG”, “High-density surface EMG”, “ Muscle fatigue”, “Repetitive movement”, “Ergonomics”, “Prolonged work”, “Dynamic tasks” and were used in all the database with the appropriate Boolean operators (such as And and Or). In addition other literature searches were also performed through google search engine and reference list of those relevant articles. Only full papers were considered and insufficient information formats, such as abstracts published in term of conference or workshop proceedings were not included.

2.2 Screening and eligibility criteria

After duplication removal, all the articles found were considered as excluded ones after being screened following these criteria:

- No related subject
- Publication before 01-01-2005
- Language not accessible
- Text not available.

Articles were considered eligible if they meet the following criteria:

- Studies which whose objectives are involved with Multi-channel surface EMG applying during the repetitive movement
- Studies which provide information about multi-channel surface EMG based muscle fatigue/muscle activity evaluation during the repetitive movement

- Studies that testify the practical application of multi-channel surface EMG in repetitive task
- All the above considered studies were performed in humans not in animals.

3. RESULTS

3.1 Study selection

The details of the selection of all relevant articles both, excluded articles and included articles were performed through several criteria, based on the PRISMA statement established for reporting systematic reviews and meta-analyses of studies (PLoS_Medicine, 2009). All those details can be shown in Figure 1.

3.2 Multi-channel surface EMG applications in muscle fatigue/muscle activity assessment over repetitive movements

Four studies were found associated with the examination of muscle fatigue/muscle activity by using Multi-channel surface EMG in repetitive movement activities (Table 1), that is considered as useful for the practical investigations of muscle fatigue/muscle activity in occupational tasks, which mostly employ the repetitive movement. In this review, the first two studies shown in Table 1 used one-dimensional of multi-channel surface EMG, and other two remaining studies applied two-dimensional of multi-channel surface EMG investigating muscle fatigue/muscle activity during the repetitive tasks. All of these studies evaluated muscle fatigue/muscle activities on upper limb of subjects' body. In summary, the evaluated muscles consisted of upper trapezius, upper, middle and lower trapezius, biceps *brachii* and lumbar elector spinae muscle respectively. Remarkably all of surface EMG electrode arrays were used with a semi-disposable adhesive grid separating electrode arrays from the skin of subjects.

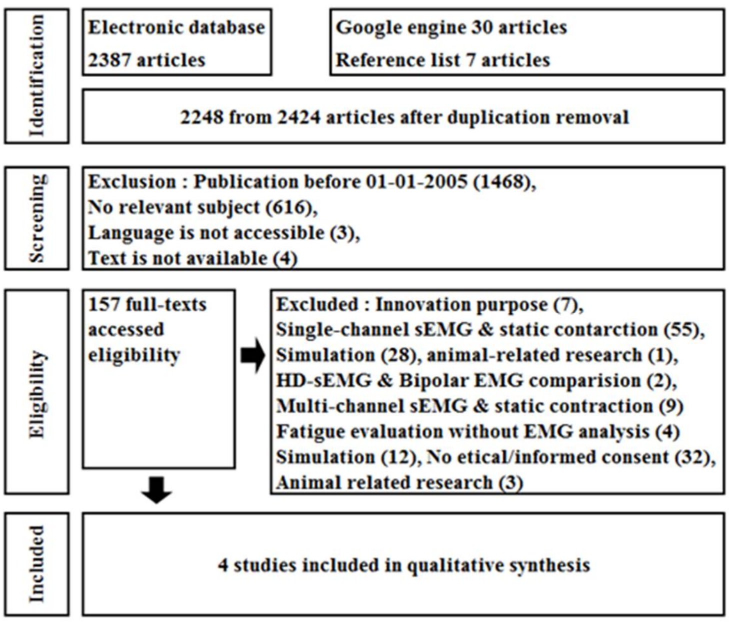

Figure 1. Selection criteria of relevant articles.

The first study from Table 1, Falla and Farina (2005) conducted the experiment to investigate muscle fibre conduction velocity (CV) compared among a group of nineteen upper trapezius muscle patients and nine healthy controls. The EMG signals were measured bilaterally by linear adhesive arrays of four electrodes (bar electrodes, 5×1 mm size, 10 mm apart) packed with a semi-disposable adhesive, separating surface EMG electrodes from subjects' skin with small cavity filled with 20-30 μL of conductive gel.

Table 1. Multi-channel surface EMG applications in repetitive movement.

Authors	Year	Type of Array electrodes	Number of Electrodes	Number of Subjects	Type of muscle
(Falla and Farina, 2005b)	2005	One-dimensional	4 (1×5)	19 Patients 9 Healthy	Upper trapezius
(Falla et al., 2007a)	2007	One-dimensional	8 (1×9)	19 Healthy	Upper, middle, lower trapezius
(Farina and Falla, 2008b)	2008	Two-dimensional	64 (13×5)	4 Healthy	Biceps brachii
(Falla et al., 2014a)	2014	Two-dimensional	64 (13×5)	19 Patients 17 Healthy	Elector spinae

The test was conducted as the subjects were performing repetitive task of tapping their hands in a cyclic manner between targets placed at mid-thigh and 120° of shoulder flexion, according to the beat of 88 beats/min generated from metronome up to 5 min. Muscle fibre conduction velocity (CV) was computed at each cycle at the time instant corresponding to 90° of flexion (Farina et al., 2004a). Instantaneous mean power spectral frequency (iMNF) was computed at the same time instants as CV value. Average rectified value (AVR) was also computed as the same time instants as CV and iMNF simultaneously achieved. The results appeared that CV decreased over time as fatigue progressed during dynamic contraction, but CV of the upper trapezius muscle was higher in people with chronic neck pain than in the control group. The iMNF also decreased over time of fatigue during dynamic contraction, but iMNF slope was greater in the patient group compared to the control group. Meanwhile the Average rectified value (AVR) increased over time of fatigue during dynamic contraction, and AVR slope was higher in the patient group compared to the control group.

The second study from Table 1, Falla and her team (2007) conducted the experiment to investigate spatial muscle activation during a dynamic cyclic task of the upper limb, consisting of upper, middle and lower division of trapezius muscle on the right hand side of thirteen healthy subjects. At the upper division of trapezius, it was applied with three consecutive electrodes, at middle division of trapezius, it was applied with two consecutive electrodes, and at the lower division of trapezius, it was applied with three consecutive electrodes. The selected surface EMG in use was linear adhesive arrays of eight electrodes (bar electrodes, 5mm×1mm size, 5 mm apart; LISiN-SPES Medica, Italy), it was used with semi-disposable adhesive, separating surface EMG electrodes from the skin with small cavity filled with 20-30 μL of conductive gel. The test was conducted as the subjects were performing repetitive task of tapping their hands in a cyclic manner between targets placed at mid-thigh and 120° of shoulder flexion, according to the beat of 88 beats/min generated from metronome up to 5 min. Instantaneous mean power spectral frequency (iMNF) was computed at time instants corresponding to 45°, 90° and 120° during the concentric phase of shoulder flexion and was estimated over 30-ms time interval (P et al., 2001) in order to reduce the variance. Average rectified value (AVR) was computed as the same time instants as iMNF estimation. The results appeared that iMNF was affected by different positions of trapezius division in the upper and lower division, namely it decreased over time as fatigue progressed during dynamic contraction, but it was different for the various locations of electrodes. For the ARV value, it was affected by position for the upper and middle division, namely it increased over time as fatigue progressed during dynamic contraction, but it was also different for the various locations of electrodes.

The third study from Table 1, Farina and Falla (2008) conducted the experiment to demonstrate the capability of multi-channel surface electromyographic (EMG) signal detection with negligible artefacts during the fast dynamic movement and to estimate muscle fibre conduction velocity, that is one of the reliable indicators, identifying muscle fatigue and indicates motor unit recruitment (Houtman et al., 2003), by using a new method of short epochs estimation. They used two-dimensional surface EMG of 64 electrodes (13×5 electrodes) packed with a semi-disposable adhesive grid of electrodes (OT Bioelettronica, Torino, Italy). Surface EMG signals were collected from four subjects' right biceps brachii muscle during horizontal elbow flexion/extension movements (rang 120-170°). Subjects were asked to perform the movement as fast and as accurately as possible for 2 min. In this study it was demonstrated for the first time that multi-channel (>50 channels) EMG can be recorded with negligible artefacts (Farina and Falla, 2008) and able to compute topographical maps from the EMG root mean square values, which can be used to investigate regional muscle activity changes. The conduction velocity estimation proposed algorithm was demonstrated by applying distal portion of 4×5 electrodes grid, using a Gaussian window with standard deviation 30 ms. This technique was beneficial to avoid the innervation zone in conduction velocity estimation and the use of the average of muscle fibre conduction velocity from the distal part of electrode grid (4×5) provided less variability (Farina et al., 2001, Farina et al., 2004a) and higher value in reliability (Farina et al., 2004b) and accuracy of conduction velocity estimation, rather than using only a few channels (Farina and Falla, 2008).

The fourth study from Table 1, Falla and her team (2014) conducted the experiment to investigate lumbar erector spinae muscle activity distribution change and pressure pain sensitivity across the low back portion, as they were performing the repetitive lifting task. The selected electrode in use was two-dimensional 13×5 grid of electrodes, packed with a semi-disposable adhesive grid of electrodes (OT Bioelettronica, Torino, Italy), that was placed over lumbar erector spinae muscle. The subjects consisted of 19 people with chronic nonspecific low back pain (LBP) and 17 healthy control individuals. The task was performed by repetitive moving a box (40×20×30 cm) with the weight of 5 kg through upward and downward direction from knee level to shoulder level as a cyclic movement, 1s of time interval for box moving and 3s for interrupted waiting interval, in total the approximate time of experiment was ~200s or about 25 cycles. Electromyography signals of Mean power spectral frequency (MF) and root mean square (RMS) were computed through each bipolar recording from adjacent, non-overlapping signal epochs of 1-second duration as described previously (R et al., 1990). And for spatial distribution of muscle activities, that were computed through RMS and MF averaged over 59 signals interpolated by a factor of 8. In addition 2 coordinates x- and y-axis for the medial-lateral and cranial-caudal directions were also separately demonstrated (D et al., 2008). The results associated to EMG estimation presented as averaged RMS values across the electrodes grid of LBP group during both lifting and lowering were significantly higher than values obtained from control group, and for the averaged MF value across the electrode grid of LBP group significantly appeared to decrease lower toward the end of the task duration. For the topographical map from EMG RMS value appeared to observe the shift of muscle activity toward caudal direction across the duration of the task particularly for the control group, but minimal change observed in the LBP group despite the appearance of its increasing of amplitude over time. Accordingly on y-coordinate of the centroid, the control group demonstrated higher value toward the end of the task.

4. DISCUSSION

From these four included studies, two were found associated with one-dimensional surface electrodes arrays with 1×5 and 1×9 electrodes respectively, and other two applying two-dimensional surface electrodes array with 13×5 electrodes. All of them were utilized to investigate muscle fatigue/muscle activities over repetitive movement.

As we all known that during the dynamic tasks, it will generate lots of movement and vibration, resulting in large artefacts over the interface between electrodes and subject's skin. However this problem itself and the progressive evolution of related researches had driven the solution to the development of adhesive linear arrays using with those either dry one-dimensional or two-dimensional metal electrode arrays, separating them from subject's skin but still maintain the electrical conductivity through the small cavities filled with 20-30 µL of conductive gel. This allows the action potential travelling along the muscle fibre, during dynamic contraction to be directly detected (Farina et al., 2004a). With this unique design, it is clearly that, the evolution of EMG signal analysis during the continuous movement, by multi-channel surface EMG is capable with negligible artefacts and enable the researchers found in this review to be achieved over such repetitive movement.

According to the study of one-dimensional surface EMG in this review, apparently there was correlation among two studies of the first and the second shown in the Table 1. It demonstrated that CV and iMNF decreased but ARV increased toward the end of the task, meanwhile patient group had a greater slope than healthy group, however the different location of the electrodes affected iMNF and ARV value, as shown in the second study. This implies that during the dynamic, cyclic task of the upper limb, muscle activity and its change over time depended on the position within the three divisions of the trapezius muscle (Falla et al., 2007). And it suggested that the multiple recorded sites are needed for the trapezius muscle investigation, due to the non-uniformity in muscle fibre distribution and/or recruitment/de-recruitment of motor units (Falla et al., 2007).

Accordingly from the finding of the second study, it had then been re-assured its own finding, through the applications of the third and fourth study respectively. With the feature of larger coverage of the electrode grids, as the results of first time demonstration of multi-channel surface EMG (>50 channels) detection with negligible artefacts during the fast dynamic task (Farina and Falla, 2008), that was used in both third and fourth study, this allows regional muscle activity change investigation through the topographic map.

Furthermore the new proposed CV estimation algorithm using a Gaussian window (short epochs) helps provide less variability (Farina et al., 2001, Farina et al., 2004a) and higher value in reliability (Farina et al., 2004b) and accuracy of conduction velocity estimation, rather than using only a few channels (Farina and Falla, 2008) such as one-dimensional array electrode, which was clearly demonstrated in the fourth study, that applied EMG RMS spatial distribution of muscle activity to differentiate muscle activity change among patients and healthy group, which couldn't be capable by using such a few-channel surface EMG.

5. CONCLUSION

As the results of this review, it is shown that there had been a progress in development of research on muscle assessment during the repetitive movement over time, and it had demonstrated that, the applications of muscle fatigue/muscle activity investigation is increasingly applicable by using multi-channel surface EMG, particularly with more effectiveness for the use of two-dimensional array electrodes type, along with its advanced mathematic algorithm, that had loomed up the muscle assessment in our daily-life applied field activities more applicable.

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Multi-channel Surface EMG for Muscle fatigue/activation evaluation in Ergonomics: A Systematic Review

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Abstract

Work-related muscle fatigue is one of the most prevalent health problems among workers. So far, the methods to precisely evaluate muscle fatigue/muscle activation are still limited, in terms of ergonomic applications. This study was carried out to examine and present the applications of muscle fatigue/muscle activation assessment during whether sustained or repetitive muscle contraction, by using multi-channel surface EMG. The systematic searches were conducted over 34 electronic databases, through the research from E-journals databases. Nine studies were found relevantly involved in sustained muscle contraction, and other five studies related to repetitive muscle contraction. Various signals evaluation methods, even new techniques and relevant parameters were demonstrated. The results showed that, by applying the multi-channel surface EMG, particularly with an array of two-dimensional electrodes type, along with its newly advanced mathematic algorithm had played a key role in terms of reducing the variability of calculations, resulted from a non-uniformity of muscle activation, and moreover it comes up with the property of spatial distribution of muscle activity monitoring, which the conventional bipolar surface EMG is not capable to cope with.

Keywords: multi-channel surface EMG; muscle fatigue; muscle activation.

1 Introduction

Muscle fatigue involved with work related musculoskeletal disorders (MSDs) has been reportedly documented in various different occupations [1]. In Europe alone, Musculoskeletal disorders (MSDs) are the most common work-related health problem, affecting millions of workers across the EU27 members with up to 25% of workers complaining about backache and 23% reporting muscular pains [2]. Still more noticeable, it appeared that, MSDs had become the main cause of work related absence across all EU27 member States [2], contributing to 40% of the costs of workers' compensation in some states, which obviously had a direct impact to the profit of the companies, and this could eventually affect all workers' employment security afterward.

Furthermore, this problem also caused a reduction of the gross domestic product (GDP) around 1.6% of the EU27 member whole nation [2]. Seemingly, if this problem can be avoided or reduced to a smaller scale, the benefits would be not just for the workers, but also for the company and might contribute to a larger scale as the country's GDP. In order to obtain this level of prevention and control, it is important to pay a special attention to the origin of this problem. MSDs are caused by so many factors, but physically mainly from manual handling, heavy physical work, awkward and static postures, movement repetition and vibration. The symptoms may gradually develop over days, weeks, months, and years, and basically, the initial warning is fatigue over the muscle being overloaded. Being under continued muscle overload, this situation often turns into pain, and consequently could first evolve into decreasing in body function, and subsequently could turn into an incapability.

Muscle fatigue is usually caused by repetitive or sustained work, short work cycles, and localized muscle loadings. Muscle fatigue leads to various physical manifestations, including a decrease in strength, performance of the task, exercise capacity, person's ability to exert force and power output [1, 3]. Muscle fatigue is a result of a chain of metabolic, structural and energetic changes in muscles due to insufficient oxygen and nutritive substances, supplied through blood circulation, as well as a result of changes in the efficiency of the nervous system [4]. When muscle contraction occurs, it results in a gradual increase of lactic acid concentration, which is a metabolic product that contributes to an intracellular pH change, responsible for muscle fatigue [4]. The only way to estimate muscle fatigue through biochemical manifestation (intracellular pH change) is to take blood samples from individuals at predefined time intervals, while performing a certain work. As a result of this method, it is only possible to have an overall fatigue value of the set of body muscles. It is commonly impossible to quantify muscle fatigue in a specific location, and apparently impossible to carry out the monitoring of muscle fatigue in the real time [4].

Since the central nervous system controls muscle force by varying the activity of the motor units through motor neuron innervation, in the form of electric potential signals, over the set of muscular cells or so called muscle fibres. It is then possible to measure such electrical activity so called electromyography (EMG) signal, activating muscle fiber in the motor unit through either invasive or non-invasive techniques of EMG evaluation. The invasive technique of EMG assessment is mostly utilized as diagnostic device in clinical assessment. It requires the insertion of needle electrodes into the muscle fibre. This technique therefore provides the highest accuracy of EMG investigation, due to its functional feature, that enables to detect electric potentials exactly close to the active muscle fibres. It seems that, this technique is absolutely perfect in term of application, however, in some cases, the use of needles insertion is neither desirable nor comfortable, for example in children clinical examination, sport or ergonomics [5]. On the other hand, the non-invasive technique of EMG assessment is not required to use such insertion of needles into the muscle fibres, but instead it requires the use of electrodes, placed over a particular muscle being investigated. Thus, this technique is most suitable for monitoring movement, neuromuscular control study and fitting with muscle changes assessment due to aging, pathology, therapy, training, immobilization, lack of gravity, occupational disorders, etc. [6]

On the other hand, the classical conventional surface EMG configuration is a single channel surface one. It is only capable to provide the investigation over a tiny area of the muscle under investigation. Moreover, it is unable to investigate the spatial distribution of muscle activity, which also unavailable in an intramuscular technique [7].

In recent years, the evolution of surface EMG technology in terms of research and development has been continuously and progressively implemented over time. The new techniques of multi-channel array of surface electrodes have been increasingly seen improved and more widely applied. These techniques allow for the possibility of investigating muscle fibres more comprehensively than obtaining from the conventional one, most likely by detecting changes over a larger muscle area. This unique feature also comes with other subsequent beneficial properties, including the capability of investigating spatial distribution of single muscle activity on a particular muscle and nearby, moreover, it also provides a visual EMG signal evaluation over time, which can implement through the topographical mapping of muscle activity [7].

Although, there have been the evolutions and developments of surface EMG technology over time so far, it is still questionable, whether this technique is capable and suitable for muscle fatigue/activation evaluation or not. This study aims to investigate the applications of multi-channel surface EMG over muscle fatigue/activation estimation, and whether it has enough potential to be applied for the evaluation of muscle fatigue/activation, particularly in ergonomics context, such as in daily working condition.

2 Methods

2.1 Search strategy

This systematic review was done according to PRISMA statement [8]. The literature searches were conducted from August 2014 to March 2015. They were performed over 34 electronic databases, including: ACM Digital Library , ACS Journals , AHA Journals , AIP Journals , AMA Journals , Annual Reviews, ASME Digital Library, BioMed Central Journals, Cambridge Journals Online, CE Database (ASCE), Directory of Open Access Journals (DOAJ), Emerald Fulltext, Geological Society of America (GSA), Highwire Press, IEEE Xplore, Informaworld (Taylor and Francis), Ingenta, IOP Journals, MetaPress, nature.com, Oxford Journals, Political Science: A SAGE Full-Text Collection, Royal Society of Chemistry, SAGE Journals Online, SciELO - Scientific Electronic Library Online, Science Magazine, ScienceDirect (eJournals), Scitation, SFX A-Z (title search), SIAM, Sociology: A SAGE Full-Text Collection, SpringerLink, The Chronicle of Higher Education, Wiley Online Library.

The used key-words were: “Multi-channel surface EMG”, “High-density surface EMG”, “ Muscle fatigue”, “Repetitive movement”, “Sustained contraction” “Ergonomics”, “Prolonged work”, “Dynamic tasks” and were used on all databases with the appropriate Boolean operators (such as *And* and *Or*). In addition, other literature searches were also performed through a Google search engine and reference lists of the relevant articles. Only full papers were considered eligible. Articles including, insufficient information formats, such as abstracts published in conference or workshop proceedings were not considered.

2.2 Screening and eligibility criteria

After duplication removal, all the remaining articles were screened. Those who correspond to the following criteria have been removed:

- Unrelated to the subject;
- Publication before 01-01-2005;
- Not written in English;
- Inaccessible full-text articles;

Articles were considered eligible once they met the following criteria:

- Studies involved in Multi-channel surface EMG and applied during repetitive movement or sustained contraction.
- Studies which provided information about multi-channel surface EMG based muscle fatigue/muscle activation evaluation during repetitive movements or sustained contraction.
- Studies that testified the practical application of multi-channel surface EMG in repetitive task or sustained muscle contraction task.
- Studies performed only on humans not on animals.

2.3 Study selection results

After the screening and eligibility processes, 13 articles were found relevant to the topic under studying, with one combined article that was applied in both sustained and repetitive muscle contraction. Nine of them focused on Multi-channel surface EMG applications in muscle fatigue/muscle activation assessment over sustained muscle contraction. The other five emphasized on Multi-channel surface EMG applications in muscle fatigue/muscle activation assessment, applied over the repetitive contraction.

All the details of the selection criteria were summarized in Figure 1.

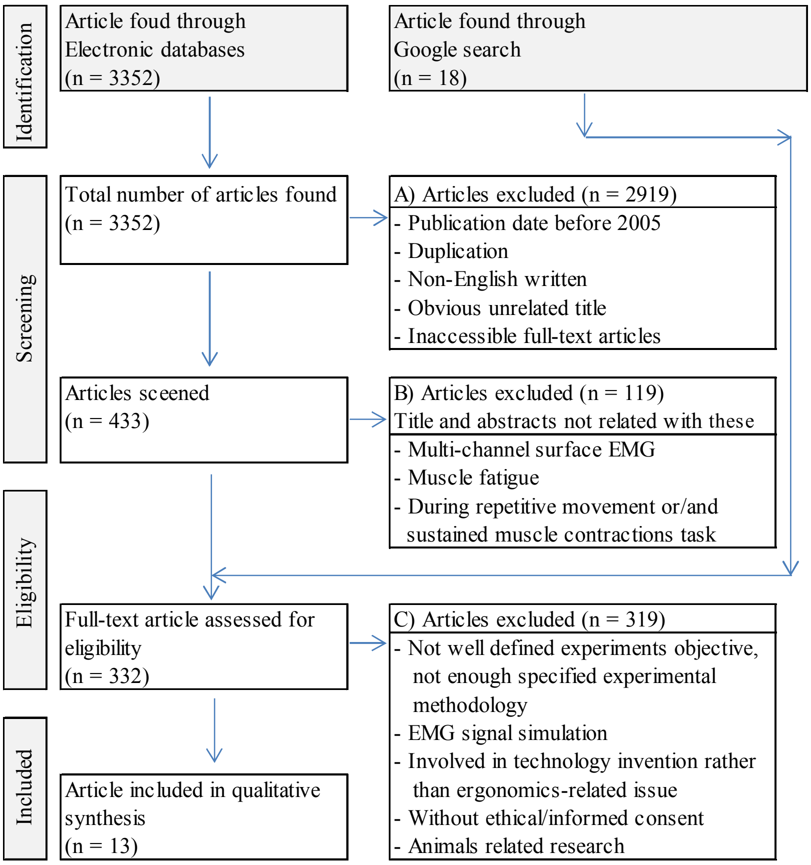

Figure 1. Selection criteria of relevant and included articles

3 Results

In order to conduct this section as easy to understand as possible, it was then organized to demonstrate separately between sustained muscle contraction and the repetitive one. Anyways, an additional found study, which is considered as interesting and might be useful for this article in term of advanced ergonomic application field, was also demonstrated exclusively.

3.1 Multi-channel surface EMG applications in muscle fatigue/muscle activation assessment over sustained muscle contraction

Nine studies were found associated with muscle fatigue/muscle activation assessment over sustained muscle contraction, evaluated by multi-channel surface EMG array electrodes (Table 1). All these studies employed either one-dimensional or two-dimensional surface EMG as a selected tool on muscle investigation. The number of electrodes in use ranged from 8 to 64. All muscle portions in these investigations were from the upper limb of subjects' body, and the upper trapezius was the most focused. The investigated EMG variables used across these included articles ranged in various ways, namely from the basic conventional indicators to the more complex ones as described as follows: root mean square value (RMS), mean spectral frequency (MNF) / median spectral frequency (MDF), conduction velocity (CV), the number of Motor Unit Action Potentials per second (MR; MUAP Rate), entropy and the centroid of RMS map or so called tomographic map. In addition, EMG signal reliability and EMG reproducibility were also investigated. From table 1, the included studies were organized sequentially according to years of publication.

Starting with the first study, Madeleine and colleagues (2006) [7] conducted the experiments on healthy subjects by investigating RMS, MNF and the centroid of RMS map, across the electrodes array during 90 s of 90° arms abduction with the elbows fully extended and the forearms pronated with the palm facing toward the ground without hand load, which is equivalent to 15% to 20% of the maximum voluntary contraction [9]. EMG variables were estimated from the upper trapezius through 4 sessions: before, during, 15 and 30 min after an intramuscular injection of hypertonic (painful) and isotonic (non-painful) saline over the cranial site. The results showed that, the RMS values increased, MNF values decreased and the centroid of RMS map moved cranially during a normal sustained contraction. But considerably, during the hypertonic and isotonic injection, compared to the before injection session, it appeared that, the RMS value decreased for the hypotonic but not for the isotonic one, and the MNF value obtained from hypertonic saline was lower than from the isotonic one. Moreover, there was a shift of the centroid of RMS map toward the caudal direction during the hypotonic injection (experimental muscle pain). And remarkably, it showed that, the centroid of RMS map moved back to the original position 15 min after the hypotonic injection, but not for the isotonic one.

The second study from table 1, Kallenberg and colleagues (2007) [10] conducted the experiments to investigate EMG variables extracted from the upper trapezius, on the healthy subjects and on the patients with chronic neck-shoulder pain, by asking them to perform a series of sustained muscle step contractions of 20 N for each step, with force ranging from 20 N to 100 N on upper trapezius, with 10 s duration for each session, then followed by 15 min rest before starting the 15 min sustained contraction on the force of 40 N, and then immediately followed by the same series of second step contraction once again. The results showed that, cases with chronic neck-shoulder pain demonstrated less myoelectric response to the fatigue task than in the healthy controls, namely RMS value increased more in controls, while CV and MDF value decreased more in controls. The MR value of both groups increased corresponding to the higher scale of the step contraction's force level, but for the first and second step of the steps contraction, MR value increased in the control group while stayed constant in the case group.

The third study from table 1, Troiano and colleagues (2008) [11] conducted the experiments to examine EMG signals of the upper trapezius on healthy subjects. It was performed through isometric sustained contraction of shoulder elevation, using experimental station without the contribution of force from the feet. The experimental protocol started from step contraction, with force ranging from 10% MVC to 80% MVC in step of 10% MVC, and lastly performed sustained contraction at 50% MVC until exhaustion. They discovered that, the surface EMG amplitude (RMS) increased during the contraction, while the MNF and the CV value decreased corresponding to the duration of the step or the endurance test progress. It was also observed that, the RMS value was largely fluctuating during the endurance test. The spatial activation pattern of the RMS map, or so called tomographic map was also investigated. It appeared that, the correlation coefficient between the maps at different levels of force and during the endurance contraction was high in all cases with Corr > 0.7. For the Entropy variable, they found that, it was significantly related to the different force level from the step contraction as well as the rate of change of the CV and MNF value, but it was not affected by the endurance test.

Table 1.

Multi-channel surface EMG array electrodes applications for muscle fatigue/muscle activation assessment over sustained muscle contraction

Authors	Year	Electrodes Type	Number of Electrode	Number of Subjects	Experimental Muscle	Investigated EMG variables
Madeleine et al. [7]	2006	2-D	64 (13×5)	10 Healthy (Male)	Upper trapezius	RMS, MNF, Centroid
Kallenberg et al. [10]	2007	2-D	16 (5×4)	10 Healthy 10 Patients (chronic pain)	Upper trapezius	RMS, MDF, CV, MR
Troiano et al. [11]	2008	2-D	64 (13×5)	14 Healthy	Upper trapezius	RMS, MDF, CV Spatial activation Entropy
Kallenberg & Hermens [12]	2008	2-D	16 (5×4)	10 Healthy 6 Healthy	Upper trapezius & *Bicep branchii*	RMS, MDF, MR
Falla et al. [13]	2008	2-D	49 (10×5)	18 Healthy (9 male, 9 female)	Upper trapezius	RMS, MDF Centroid
Farina et al. [14]	2008	2-D	64 (13×5)	11 Healthy	Upper trapezius	Entropy, Centroid
Kallenberg et al. [15] (Combined with Table 2)	2009	1-D	8 (1×9)	12 Healthy	Upper-trapezius & Sternocleidomastoid	RMS, MDF, EMG-Reproducibility
Falla et al. [16]	2010	2-D	49 (10×5)	10 Healthy 10 Patients (fibromyalgia)	Upper trapezius	RMS, MDF Centroid
Barbero et al. [17]	2011	2-D	64 (13×5)	10 Healthy	Upper trapezius	Reliability of EMG

Remark: 1-D = One-dimensional, 2-D = Two-dimensional,

The forth study from table 1, Kallenberg and Hermens (2008) [12] set up two experimental tasks. The first one was arranged to perform the upper trapezius step sustained contraction of shoulder elevation, by the force starting from 20 N to 100 N with 20 N each step. And the second one was designed to perform a 10% MVC sustained isometric contraction of *biceps brachii* muscle for 15 min. According to the results, on the first experiment RMS and MR value increased approximately and linearly along the rising step contractions, noticeably the sensitivity of MR for change in force (expressed as the normalized slope of the regression line) was almost twice the one obtained from RMS. For the second experiment, it was observed that MDF value decreased over time, while RMS and MR value increased over time as the test progressed, but MR value increased considerably less than the RMS. Furthermore it is obvious that, MR increased slightly while RMS increased so strongly.

The fifth study from table 1, Falla and colleagues (2008) [13] conducted an experiment by asking 9 healthy male and 9 healthy female subjects to hold their shoulder abducted and sustained at 90° with the elbows fully extended and the forearms pronated with palms facing toward the ground for 60 s. With this position, it creates approximately 15% to 20% of maximum voluntary contraction [9]. Afterwards they launched EMG measurement on the upper trapezius before and after the injection of 0.4 ml. of hypertonic (painful) and isotonic (control) saline into the cranial region of the upper trapezius muscle. They found that, the average MNF value decreased over time in both men and women over all conditions, and it was remarkably reduced following the injection of hypertonic saline compared to both baseline and isotonic saline conditions for both genders. For the average RMS value of both men and women, it was found reduced following the injection of hypertonic saline, compared to both baseline and isotonic saline conditions. Meanwhile average RMS value of men remained constant over time, on the contrary, the average RMS value of woman increased overtime during the non-painful conditions (baseline and isotonic saline injection). For the centroid of tomographic map, it was observed a shift toward the cranial region in all the above conditions of both men and women, except for the condition of women with hypotonic injection (painful), which appeared to remain constant.

The sixth study from table 1, Farina and colleagues (2008) [14] conducted the experiment by investigating changes in spatial distribution of EMG parameters of the upper trapezius using a 13×5 electrodes grid. The 11 healthy subjects were positioned comfortably on a chair with their feet parallel on the floor, and performing the static contractions of shoulders 90° abduction until reaching the endurance failure. The performing was implemented in detail with elbows fully extended and the forearms 90° pronated, maintaining the palm facing toward the ground and without hand load. According to the previous information, this 90° shoulder abduction corresponds to 15% to 20% of MVC or approximately 14.5 ± 1 N [9]. The results revealed that, the centroid moved toward the cranial direction over time, as the endurance experiment progressed, namely y-axis coordinate (cranial - caudal direction) of the root mean square map decreased. Noticeably the x-axis coordinate (lateral-medial direction) also increased by shifting toward medial direction over time, however, the absolute shift of the x-axis coordinate over time was negligible with respect to the shift of y-axis coordinate. In addition, the shift of the centroid was positively correlated with the percentage variation in the average root mean square (over the grid), with respect to the beginning of the contraction. For the entropy (degree of uniformity) value of the RMS distribution map, it appeared to significantly decrease over time as the endurance test progressed, with respect to the initial value.

The seventh study from table 1, Kallenberg and colleagues (2009) [15] conducted the experiment to determine the reproducibility of EMG variables, obtained from the array surface EMG recording. All participants were from 12 healthy subjects and the focused study portion was shoulder and neck muscle, contracting during the different functional tasks (in this case, only sustained contraction tasks were accounted). The experimental protocols were done through the evaluation of EMG variables, obtained from within-day and between-day recording, as well as the agreement of EMG variables which were also verified. On these considered cases, the experimental task was a sustained contraction of 90° shoulder abduction with the elbows fully extended (investigating upper trapezius), which was held for 10 s. And the sustained contraction of the sternocleidomastoid (SCM), which was achieved by rotating their head to the non-dominant side, while maintaining a constant neck flexion/extension for 10 s. The results revealed that, for the reliability indicator, which was processed through the Intra-class correlation coefficients (ICC), it appeared that, ICC value of the amplitude-related (RMS) and the frequency-related (MDF, MNF) variables (except MR) were higher than 0.7, which in general with the value of 0.6 is normally considered accepted as a good reliability. For the EMG variable agreement indication, the smallest detectable change (SDC) value was found clearly lower for the frequency-related than the amplitude-related variable, which indicated that, the frequency-related variable was greater in degree of agreement than the amplitude-related. Besides, generally within-day agreement degree is higher than the between-day one.

For the eighth study from table 1, Falla and colleagues (2010) [16] performed the experiments on two groups of subjects consisting of a healthy and a diagnosed fibromyalgia one. The experimental protocol starting by, they were asked to perform the isometric shoulder abduction for 60 s, by holding both arms in 90° with the elbows fully extended and the forearms pronated with palms facing toward the ground. In addition, the healthy control group was asked to repeat the abduction task following the injection of the hypertonic (painful condition) and the isotonic (non-painful condition) saline into the upper trapezius muscle. The results illustrated that, during the sustained contraction, the control healthy group showed an increase of the EMG average amplitude, which occurred shifting relatively further toward the cranial region direction than in the caudal one. Meanwhile, in the patient group, lower average EMG amplitude was observed than occurring in the control group. Remarkably, the significant shift of the centroid of the RMS distribution map, toward the cranial direction during the experiment was not found in the patient group, corresponding to, what occurred in the painful condition of the control group, following the injection of the hypertonic saline.

For the ninth study from table 1, Barbero and colleagues (2011) [17] conducted the experiment aiming to prove the reliability of the surface EMG matrix in locating an innervation zone of the upper trapezius muscle. The intra and inter-rater value were selected as indicators of the reliability of the investigation. Ten healthy subjects were instructed to perform a series of isometric contractions of upper trapezius muscle by two trained operators. The subjects were asked to perform a shoulder elevation, by pulling upwards on both sides handles simultaneously. In addition, these two trained operators were also responsible to independently estimate the innervation zone, by the visual analysis. The results showed that, there was an almost perfect agreement between the two operators on intra-rater and inter-rater reliability evaluation. Namely, for the Intra-rater reliability analysis: the percentage of agreement of operator “A” was 91.5% with Kappa = 0.90, while the percentage of agreement of operator “B” was 93% with Kappa = 0.92. At the meantime, the Inter-rater reliability analysis of both operators had percentage of agreement of 98% with Kappa = 0.82.

3.2 Multi-channel surface EMG applications in muscle fatigue/muscle activation assessment over repetitive contraction

Five studies were found associated with muscle fatigue/muscle activation assessment over repetitive contraction, assessed by multi-channel surface EMG electrodes array (Table 2). All these studies employed either one-dimensional or two-dimensional surface EMG as a selected tool. The number of electrodes in use, ranged from 8 to 64 electrodes. All muscle portions in these investigations were from the upper limb of subjects' body, and the upper trapezius was the most focused one. The investigated EMG variables used across these included articles ranged in various ways, namely from the basic conventional indicators to the more complex ones, as described as follows: root mean square value (RMS), averaged rectified value (ARV), instant mean spectral frequency (iMNF), instant median spectral frequency (iMDF), conduction velocity (CV), and centroid of the RMS map or so called tomographic map. In addition, the EMG signal reliability and the EMG reproducibility were also investigated. From table 2, the included studies were sequentially organized according to years of publication.

The first study from table 2, Falla and Farina (2005) [18] conducted the experiments to investigate the average muscle fibre conduction velocity (CV) and its change over time in upper trapezius muscle. It was conducted among healthy controls and the patients with chronic neck pain condition. The one-dimensional of 4 electrodes array was used as a selected electrode. Subjects were asked to perform the experimental task of the repetitive movement, by tapping their hands in a cyclic manner between the targets, which was positioned at the mid-thigh and at 120° of the shoulder flexion repetitively. Those movements were made at the frequency of 88 beats/min, generated by a metronome for as long as 5 min. They found that, the averaged CV decreased over time as the experimental task progressed in the patients group. Considerably the averaged CV during the beginning of the task was higher in the chronic neck pain than in the control group. Significantly the CV value of each cycle in this study was determined at the time instant corresponding to 90° of flexion, according to the method proposed by Farina et al. [19]. Furthermore, they also observed that, the iMNF value tended to decrease over time as the experimental task progressed, but the slope and the normalized slope of the patient group was observed greater than in the control group. For the ARV value, it tended to increase over time as the experimental task progressed, but the slope and the normalized slope of the patient group were greater than in the control group. Remarkably, for the signal analysis of the iMNF and the ARV indicator, in order to reduce the estimation variance, they were therefore estimated over the time interval of 30 ms and 250 ms respectively. It was done by centring those above calculated time interval at the same time instant of the CV estimation. In addition, all involved variables were averaged in 10 values, each value represented each consecutive non-overlapping interval of 10% of endurance time [18].

Table 2.

Multi-channel surface EMG array electrodes applications for muscle fatigue/muscle activation assessment over repetitive muscle contraction

Authors	Year	Electrode Type	Number of Electrodes	Number of Subjects	Experimental Muscle	Investigated EMG variables
Falla & Farina [18]	2005	1-D	4 (1×5)	9 Healthy 19 Patients (chronic pain)	Upper trapezius	CV, iMNF, ARV
Falla et al. [20]	2007	1-D	8 (1×9)	13 healthy	Upper trapezius Lower trapezius	iMNF, ARV
Farina & Falla [22]	2008	2-D	64 (13×5)	4 healthy	*Biceps brachii*	CV
Kallenberg et al. [15] (Combined with Table 1)	2009	1-D	8 (1×9)	12 Healthy	Upper-trapezius	RMS, MDF, EMG-Reproducibility
Falla et al. [23]	2014	2-D	64 (13×5)	17 Healthy 19 Patients (LBP)	Lumbar elector *spinae*	RMS, MNF Centroid

Remark: 1-D = One-dimensional, 2-D = Two-dimensional,

The second study from table 2, Falla and colleagues (2007) [20] conducted the experiment to investigate changes in spatial muscle activation over three different trapezius muscle divisions, including: upper division (assessed by three consecutive 5 × 1 array electrodes), middle division (assessed by two consecutive 5 × 1 array electrodes) and lower division (assessed by three consecutive 5 × 1 array electrodes). All were done during the repetitive dynamic task. The electrodes array was attached with the semi-disposable adhesive, separating those electrodes from the skin with small cavities, filled with 20-30 µL of conductive gel. The experiment was conducted through the repetitive task of tapping their hands in a cyclic manner between targets positioned at mid-thigh and at 120° of the shoulder flexion. Those movements were made at the frequency of 88 beats/min, provided by a metronome for as long as 5 min. The instantaneous mean power spectral frequency (iMNF) was computed at the time instants corresponding to 45°, 90° and 120° during the concentric phase of the shoulder flexion. In order to reduce the calculation variance, each iMNF value was estimated over 30 ms of time interval [20, 21]. The average rectified value (AVR) was computed at the same time instants of the iMNF estimation. The results showed that, the iMNF value was affected by the different location of the trapezius division, including the upper and the lower one. The iMNF value decreased over time as fatigue developed during the dynamic contraction, and the greater decrease was mainly observed in the cranial direction, with respect to the caudal one. For the ARV value, it was affected by the location of the upper and the middle division, in other words, it increased over time as fatigue progressed during the repetitive dynamic contraction. For the ARV rate of change and the normalized rate of change, they were observed the greatest value at the far most cranial direction in the upper division.

The third study from table 2, Farina and Falla (2008) [22] set up the experiment to prove the capability of two dimensional multi-channel surface EMG, which was utilized in fast dynamic movement. The experimental task was fast dynamic horizontal elbow flexion/extension, conducted for 2 min at the maximum speed, with the angle of movement cyclically ranging from 120° to 170°. The silver-silver chloride interfaces of 13 × 5 electrodes array was separated from the skin by small cavities, filled with the conductive gel across the semi-disposable adhesive array (also acting as a buffer in the event of movement) [2]. The muscle fiber conduction velocity (CV) was calculated at the time instant corresponding to 165° of elbow extension, which is usually presented the maximum EMG amplitude [22]. In this study, the research team had proposed the new method of short epoch for the calculation of the conduction velocity through its proposed algorithm. It was implemented by taking distal portion of 4 × 5 electrodes grid, using a Gaussian window with standard deviation of 30 ms. This technique was beneficial to avoid the innervation zone from involving in the conduction velocity estimation. With this unique technique, it had become the first time event, that the multi-channel (>50 channels) EMG was capable to estimate EMG variables, with the negligible artefacts during the fast dynamic contraction. The results of this experiment revealed that, the extracted CV value's standard deviation was obviously reduced from the range of 0.20 m/s to 0.33 m/s once using only one column to as less as 0.02 m/s to 0.15 m/s when applying all 5 columns in the calculation.

The fourth study from table 2. (partial experiment from the study No. 7 of table 1). Kallenberg and colleagues (2009) [15] set up the experiment to determine the reproducibility and the agreement of EMG variables, extracted from surface EMG electrodes array. The experimental protocols were done through the evaluation of EMG variables, obtained from within-day and between-day recording. In this case, the experimental task was an ironing activity that acted as a simulation of the repetitive movement, focused mainly on the upper trapezius. The simulation task was done through the moving of their dominant hand between the two dots, marked on a solid horizontal surface, and located in front of the subjects. It was performed for 1 min long, with the frequency of 70 bpm generated by a metronome. The reliability indicator used in this study was the Intra-class correlation coefficients (ICC) and the EMG variables agreement indication, which is represented by the relative smallest detectable change (SDC) indicator. The results revealed that, ICC value of the amplitude-related and the frequency-related variable (excepted MR) were higher than 0.7, which in general, with the value of 0.6 is already considered as accepted as a good reliability. For the SDC values of this ironing task, it was observed relatively high (representing a poor agreement) with respect to the one in sustained contraction, observed in study No 7 in table 1. In addition, it also appeared that, the within-day recording a greater degree of agreement than in the between-day.

The fifth study from table 2, Falla and colleagues (2014) [23] conducted the experiment to investigate the healthy and the patients group suffering with LBP. The muscle activity distribution of the lumbar erector *spinae* was assessed as the EMG parameters by using a 13 × 5 electrodes grid. Subjects were asked to perform a repetitive box moving with the weight of 5 kg. The box moving procedure was performed through the upward and downward direction, with the level ranging from knee to shoulder as a cyclic movement. The moving cycle time interval was set: 1 s for the box moving and 3 s for the waiting time between each cycle. In total, the approximate time interval of the experiment was ~200 s or approximately 25 cycles. The mean power spectral frequency (MNF), root mean square (RMS) and the tomographic map of the EMG amplitude were computed. The values of RMS, MNF and the x-axis and y-axis coordinate of the centroid of RMS tomographic map were calculated over 1-second window, and were centred at the maximum lifting and lowering speed of each task cycle. The results showed that, the averaged RMS value (averaged across the entire grid of electrodes) increased significantly and obtained the higher value at the end of the task for LBP group, during both lifting and lowering. At the meantime, the MNF value decreased significantly and was observed the lowest at the end of the lowering task. However no significant change of either RMS or MNF value was found in the control group, whether from the lifting or the lowering task. For the representative tomographic map of RMS value, the result demonstrated that, the centroid shifted significantly toward the caudal direction, as represented by the shift of the y-axis coordinate of the centroid (mm) over the lumbar elector *spinae* portion, which occurred in both lifting and lowering task of the control group. Whereas, the very less change was found in the LBP one, considerably, despite it was observed the increase of the RMS value overtime in LBP case. On the other hand, no significant change was found in x-axis coordinate of the centroid of RMS tomographic map in both control and LBP group.

3.3 Additional interesting found studies

Although this systematic review was conducted based on the issue of muscle fatigue/activation evaluation, using multi-channel surface EMG, however, during the research process, a study associated with the clinical application was also found. Considerably, it was interesting and useful for obtaining more comprehensive insight in an advanced ergonomic application field. Therefore, it was exclusively selected and will be presented briefly as following: Kallenberg and colleagues (2006) [24] conducted the research to investigate the possibility of the distinction between computer workers with (case) and without (control) work-related neck-shoulder complaints, evaluated based on multiple surface EMG parameters. Fourteen controls and thirteen cases were asked to perform five tasks consisting of: a unilateral dynamic hand task, a typing task, an editing task, a mouse task and a stress task.

The EMG signals were measured from trapezius muscle by linear 8 channel electrode arrays (one-dimensional), and were determined for RMS, MDF, MUAP rate (MR), MUAP shape properties. The statistic tool, called logistic regression analysis, was applied to select the most discriminating parameters. Afterward, these parameters were combined in a model for each of those five different tasks. The results revealed that, the MUAP-related parameters became the most discriminative one, and the most discriminative model was mouse task, with correct classification of 87% (jack-knife evaluation). Kallenberg research team concluded that, with this technique, the combination of multiple surface EMG parameters was capable of distinguishing the computer workers, whether with or without neck-shoulder complaints in such small pilot sample.

4 Discussion

This study reviewed the applications of multi-channel surface EMG electrodes in muscle static sustained contraction and repetitive dynamic contraction. The discovered findings from both were likely in correspondence with each other, considerably supporting and enhancing the understanding of muscle fatigue/muscle activation, as discussed in the below sections.

4.1 Multi-channel surface EMG & Muscle fatigue/muscle activation phenomena in sustained muscle contraction

By studying the multi-channel surface EMG & Muscle fatigue/muscle activation phenomena in sustained muscle contraction (Table 1), it was evidenced that, there were many EMG parameters involved in this review. Therefore, in order to obtain an easier insight, the following discussion points were conducted, according to the classification of EMG parameter groupings. Accordingly for this study, it could be classified roughly in amplitude-related, frequency-related, conduction velocity, MR (MUAPs Rate), spatial distribution and reliability & reproducibility respectively.

4.1.1 The amplitude-related parameters

In this review, it was found that, the RMS value in sustained muscle contraction, which was calculated by averaging through all the electrodes grid, was capable to obtain a lower estimated variance. This is according to the principle of: the larger number of channels, the lower variance is estimated. It appeared that, the RMS value increased over time as fatigue developed.

In study No. 1, RMS increased continually during the intense static contraction in a normal condition (non-painful), which was in agreement with all studies involved with the same parameter evaluation consisting of: study No 2, 3, 4, 5, 7 and 8 from table 1. As a result of the size principle [25], once muscle loses power against the sustained load, additional motor unit (MUs) will be recruited with the higher-threshold MUs and larger size. Consequently, this contributed to an increase in RMS [10, 26]. But remarkably during the painful condition (injected hypertonic saline) in study No 1, the RMS value appeared to be lower than in the non-painful one. This was also in line with the second study in table 1, during the sustained contraction, the RMS value of the chronic neck-shoulder pain subjects showed less increase in RMS value than in the healthy controls. In study No 3, of table 1, RMS value (from the healthy subjects) was also rising over time during the sustained contraction, and noticeably the high fluctuation was also observed. In order to reduce the calculation error resulting from those fluctuations, it is possible to obtain the more precise estimation by using the larger epochs than the smaller one. However, it is likely that, it could be feasible only to distinguish in a quite different force level [11].

Accordingly, in the study No 4, RMS values also increased along with the rising force of the step contraction (Please see the connection with MR result in 4.1.3). In the study No 5, it showed that, gender influenced the RMS manifestation, regarding to the RMS of male subjects tended to remain constant during the 60s of sustained shoulder abduction, whereas, it was observed increasing in the female subjects, during the baseline/non-painful condition. In addition, another result from study No 5 was also found supporting for more evidence to study No 1 and 2, regarding to the finding of the lower RMS value, observed during the hypertonic injection (painful condition), with respect to the baseline and non-painful one. Study No 8 in table 1 provided the best supporting evidence of all painful-related studies (compared with study No 1, 2 and 5), namely the RMS value in painful condition (healthy with hypertonic injection) was lower than in the non-painful one (baseline/isotonic injection). Considerably, it also correlated with the values obtained from the diagnosed fibromyalgia patients, which could most likely be due to the reduction of descending drive to the muscle. This suggested that, the nociceptive input to the spinal and *supraspinal* circuitries plays the key role in reducing activity of the upper trapezius, preventing it from turning into the impaired muscle and fatigue afterward [15]. By this way, it is clearly seen in the altered motor strategies, appearing on the healthy non-painful condition that had distributed the overloaded muscle activation across the cranial direction (please see relevant details in 4.1.5).

4.1.2 The frequency-related parameters

In this review, the frequency-related parameters consist of MDF and MNF. The results appeared that, the frequency-related parameters tended to decrease over time as the muscle fatigue developed during the sustained contraction, as evidenced in studies: No. 1, 2, 3, 4, 5, 7 and 8 in table 1.

Remarkably, in study No 1, the MNF value declined over time as fatigue progressed, but it was observed the higher value in hypotonic saline injection (painful condition), compared with the isotonic saline injection (non-painful condition). This was in agreement with the study No 2 finding, stating that, the healthy controls and patients with neck-shoulder pain showed the declination of MNF overtime, as fatigue progressed. However, the patients had a higher value than the value obtained from the healthy controls. This phenomenon may have been due to the counteracting mechanisms, seemingly attempting to maintain a constant force level, while the motor unit discharge rate decreasing, as a result of the muscle pain. Therefore, the other muscles may have played an important role in involving in redistribution among whether in the rhomboid major, minor and the transvers part of the trapezius and *levator* scapulae muscle [7, 27].

The crosstalk, generated from these other involving muscles, may have impacted the EMG activity that was detected by the electrodes grid. Since crosstalk signals characterize as high frequency components, this may have driven the mean power spectral frequency level relatively higher, with respect to the normal case [7, 28, 29]. However, if consider more comprehensively, there are many factors influencing the EMG frequency-related parameters manifestation, such as: subcutaneous fat, muscle length, temperature, action potential conduction velocity, firing rate, velocity of contraction, activation level, type of contraction and synchronization of active motor units [10].

4.1.3 The MR (MUAPs Rate)

The fatigue-related MR (MUAPs Rate) parameter was found increasing during the sustained contraction, whether in the study No. 2 and 4 in table 1. This phenomenon could be explained as the recruitment of new motor units and the increase of firing rates of those new recruited motor units [12].

It was also observed that, the MR parameter was more sensitive to changes in the shoulder muscle contraction at low to moderate force step than in the RMS one. This occurs due to, at higher force levels, it could be affected by the overlapping of MUAPs among each other, while the number of MUAPs were increasing. Considerably, this phenomenon, which is caused by the increase of the rate of firing, takes place in response to regaining the power back against the constant load, generally resulting in the underestimation of MUAPs number [12, 30]. Moreover, the new recruited MUs usually come with the bigger size, which contributes to the higher force output per firing.

Consequently, the less additional MUs and/or firings are needed, which could result in the declination of the MR estimation. From this finding, it might be concluded that, the MR parameter is greatly dominated by motor control properties, whereas, the RMS one is largely influenced by MU size [12]. This same evidence was also found in the study No 4, on the issue of a difference between MR and RMS value at the same force level of the repeated step 2 contraction. Which it appeared that, the RMS value was rising higher, while the MR value still remained at the same level.

4.1.4 The conduction velocity

Conduction velocity of MUAPs is one of the reliable indications for fatigue estimation [31]. Once muscle fatigue occurred, CV value tended to decrease over time in the controls healthy group, during the sustained contraction, as demonstrated in the study No 2 and 3. Considerably, subjects with chronic neck-shoulder pain showed a constant CV value or just a slightly increased one, as revealed in the study No 2. This phenomenon may have been due to the change of the peripheral muscle fibre properties (including: muscle fibre CV, cell membrane properties etc.) occurring in the painful chronically fatigued muscle, which took place since the beginning of the task [10]. This finding also supports the hypothesis that, cases with chronic pain show less signs of fatigue, which is in agreement with the previous studies [32, 33].

4.1.5 The spatial distribution & entropy

The spatial distribution of EMG activity was generally identified by the centroid of the RMS map, and during the sustained contraction, it was found shifting toward the cranial direction of the upper trapezius muscle in a normal or non-painful condition. This shifting of centroid was more clearly presented on the y-coordinate (cranial-caudal direction), however, in the x-axis coordinate or medial-lateral direction, it was also observed the shift of the centroid toward the medial direction. Nevertheless, due to its very less shifting length, then it was negligible with respect to the shift from y-axis coordinate [14].

This finding was in line with the other related studies, including: study No.1, 3, 5 and 6 in table 1. The appearance of this phenomenal may have been due to an efficient strategy in maintaining the constant force, which is required in the sustain contraction. This efficient strategy can be accomplished through a distribution of muscle activity across the different regions of muscle, rather than maintaining that overloading muscle activation over the same particular muscle region [34, 13].

Considerably, in study No 1, the centroid of RMS map moved toward the cranial direction as expected during the non-painful condition (baseline and isotonic injection). Whereas, after the injection of hypertonic saline (painful condition) at the cranial site, the centroid of RMS map turned to move caudally. This apparently corresponded to the study No 5 in non-painful (baseline or isotonic injection) sustained contraction of both male and female group. However, it was in contrast with the case from female in painful condition (hypertonic injection), which appeared that, its centroid of RMS map position remained constant in place. By these, it could be concluded that, gender may affect the fatigue phenomenon, namely, muscle pain may alter the normal adaptation of upper trapezius muscle activity on fatigue in women but not in men. Moreover, the shift of the centroid of RMS map is also in line with the study No 6, which revealed that, this centroid of RMS map shift was accordingly related to the endurance time. By this, it suggested that, the muscle activity distribution plays a key role on the strategy to maintain a static contraction [14].

Anyways, it appeared that, the shift of the centroid of RMS map was conversely correlated to the entropy value, namely subjects with longer endurance time, which will have a larger shift of centroid of RMS map toward the cranial direction. This resulted in the less uniformity of root mean square maps, which reflected in the less value of entropy, with respect to in the beginning period of the sustained contraction. However, in the study No 3, they found no significant change of an entropy over time during the sustained contraction of 50% MVC, but instead they did observe a significant change during the step contraction with different forces.

4.1.6 The reliability

From study No. 7 in table 1, the EMG variable of the reliability indicator used in an investigation was ICC (Intra-class correlation coefficients). The finding suggested that, both amplitude-related (RMS) and frequency-related (MNF or MDF) were in good reliability (the obtained score higher than 0.7; while 0.6 is already considered as a good reliability). Meanwhile, an EMG variable agreement indicator used in this study was SDC (smallest detectable change). The SDC value of the frequency-related parameter was found lower than the amplitude-related one. This suggests that, the frequency-related parameters are in higher degree of agreement than the amplitude-related one. By this, it implies the more suitable investigation for the intervention which aims to modify motor control [15].

Furthermore, EMG variables obtained from within-day are greater in agreement with respect to the ones obtained during the between-days, as revealed from the lower value of the within-day SDC than in the between-day. In addition, the reliability of an innervation zone identification in the study No 9 of table 1, which demonstrated the almost perfect agreement between the two trained operators, as shown in the intra-rater reliability (reliability within each operator) and inter-rater reliability (reliability between two operators) [17]. In conclusion, these findings provided the great evidences on the validation of the reliability of EMG variables and the innervation zone identification, which was likely to be verified for the further applications in the future.

4.2 Multi-channel surface EMG & Muscle fatigue/muscle activation phenomena in repetitive muscle contraction

By studying the multi-channel surface EMG & Muscle fatigue/muscle activation phenomena in repetitive muscle contraction (Table 2), it was evidenced that, during the dynamic tasks, it will generate lots of whether movement, muscle flexion/extension and vibration. These result in large artefacts occurring over an interface between the electrodes and the subject's skin, which generates a lot of noise interfering in the desired EMG signal. However, it appeared from the review that, this source of obstacle had been achieved through the development of the adhesive linear arrays, applied with whether dry one-dimensional or two-dimensional metal electrode arrays.

Using this technique, it comes up with the properties of separating of metal electrode from the subject's skin, while still maintaining the electrical conductivity through the small cavities, filled with the 20-30 μL of conductive gel. By utilizing this way, it allows the muscle action potential, which is travelling along the muscle fibre during the dynamic contraction, to be directly detected throughout all electrodes [19]. It consequently appears that, multi-channel surface EMG recording is capable of accomplishment with negligible artefacts, as the evidences which could be explained in detail below. Anyways, in this particular case, the detailed evidences could be classified roughly into different EMG parameter groupings as: amplitude-related, frequency-related, conduction velocity, spatial distribution and the reliability respectively.

4.2.1 The amplitude-related parameters

In this review, The ARV and RMS value were examined during the repetitive muscle contraction. It appeared that, their values tended to increase toward the end of the task, particularly in the subjects with the problem of chronic pain, which is suffering on the muscle being investigated [17, 23]. However, in some studies, no significant change of amplitude-related parameter was found in the healthy control [23]. This could likely be explained as a result of the nature of the dynamic task that may contribute to maintaining of the blood flow throughout the muscle being activated. Subsequently, this could play a key role of reducing the accumulation of the metabolites, which reflect the muscle fatigue. Furthermore, the set up task periods were also considered as quite short for observing any sign of muscle fatigue.

The different locations of the electrode placement appeared to affect the quality of the detected EMG signals, as shown in the study No 2 in table 2. Noticeably, it showed that, the ARV had a significant effect on whether upper and middle division of trapezius [20], and even over the same division itself, the different values of the amplitude were also detected. The evidences were demonstrated through the rate of change and the normalized rate of change of the ARV values, which were found greater in the farther cranial direction of the upper trapezius. By these, it does suggest that, the multi-channel surface EMG utilization is necessarily required for an EMG evaluation, in response to minimizing the variation of relevant calculations to be as low as possible.

4.2.2 The frequency-related parameters

In this review, all frequency-related parameters consisting of MNF/MDF were evaluated during the repetitive muscle contraction. The results unveiled that, MNF/MDF values tended to decrease toward the end of the task, particularly on the subjects with problem of chronic pain over the muscle being investigated [17, 23]. However in some studies, no significant changes of frequency-related parameters were found in healthy control [23]. This might be due to the same reason, previously explained in the amplitude-related parameters presenting above (influence of dynamic task, which contributing to maintaining the blood flow).

Considerably, the different location of the electrode placement also affected the precision of the EMG signal detection and its estimation of the frequency-related parameters, as demonstrated in the study No 2 in table 2. It showed the significant effect over the frequency-related parameter, obtained from the upper and lower division of trapezius [20], and even on the same division itself, the different value of frequency-related parameters were also observed. The farther in cranial direction, the greater value it became, for the MNF value rate of change and the normalized rate of change respectively.

By these, it definitely supports the finding from the amplitude-related parameter, suggesting that, multi-channel surface EMG is crucially needed for an EMG evaluation, in term of minimizing as low calculated variation as possible. Moreover, considering both amplitude and frequency -related parameters, it seems that, the upper trapezius is likely the most proper location for an investigation of the upper limb activity, particularly in the dynamic cyclic task (both amplitude and frequency -related parameters had effect in combination only on the upper trapezius).

4.2.3 The conduction velocity

In this review, the conduction velocity parameter in the repetitive contraction tended to decrease over time during the endurance experiment of patients with chronic neck pain, moreover, its value was observed higher than in the healthy controls, as shown in the study No 1 in table 2. Meanwhile, the value of healthy control was found no significant change, which may have resulted from the same reasons, as already described in section 4.2.1 and 4.2.2). By these, it suggested that, histological and morphological change in trapezius muscle of the neck pain patients may play a major role on altering of the control strategy of the muscle mechanism, over the achievement of this dynamic task [17]. In addition, this could likely be explained as: the higher value of CV in the patients (particularly during the beginning of the task) with respect to the healthy control is related to the increasing size of the upper trapezius muscle fibre's diameter, together with the modifications of the recruited motor unit pool explaining as: the increasing recruitment of the type II motor unit, which seems to counteract some damages suffering from type I of the patients with chronic trapezius myalgia [18, 35, 36]. This is also in line with other found evidence suggesting that an overall increase in fibre diameter is associated to an increase in CV [37]. Furthermore, in order to obtain the most precise estimation of CV in the fast dynamic task, multiple electrodes grid is truly required, since there is non-uniformity of the muscle activity across the muscle different regions.

Study No 3, demonstrated for the first time of the utilization of the multi-channel surface EMG (>50 channels), in detection of EMG signals with negligible artifacts during the fast dynamic task [22]. By using the unique feature of larger detection coverage of the electrodes grid, it allows the investigation of regional muscle activity changes through analysing of the topographic map. Furthermore, the new proposed CV estimation algorithm, using a Gaussian window (short epochs), proved to provide less variability [19, 38], higher value in reliability [39], and accuracy of conduction velocity estimation than using only a few channels one [22], such as the one-dimensional array electrode.

4.2.4 The spatial distribution

In this review, the spatial distribution evaluation was found in the study No 5 in table 2, investigating the lumbar erector *spinae* muscle. The shift of the centroid of RMS map in this case moved further caudally toward the end of the task, for the healthy control. Whereas, it was observed remained unaltered in LBP group. This finding suggested that, the change of muscle activity across different regions toward the caudal direction may reflect an efficient strategy in maintaining the motor output during the repetitive movement. It is likely that, this mechanism provides an ability of a prolonged endurance attempt against the muscle fatigue [23]. Furthermore, it is so useful in term of reducing the regional overloaded muscle fibres, particularly, it is more efficient at the beginning of the task. On the other hand, the impaired alteration mechanism of the regional muscle, occurring in the LBP group, resulted in an inability of the muscle activation distribution, which should have been applied across the different regions as occurring in the healthy one. Consequently, it caused the physical overload occurring on the active muscle fiber in the LBP group, which contributed to the perpetuation or recurrence of LBP condition [23].

4.2.5 The reliability

From study No. 3 in table 2, EMG variable reliability indicator used in the investigation was ICC (Intra-class correlation coefficients). The finding suggested that, both amplitude-related (RMS) and frequency-related (MNF, MDF) obtained a good reliability (the obtained score was higher than 0.7; while 0.6 is already considered as a good reliability). Meanwhile, the EMG variable agreement indicator used in this study was the SDC value (smallest detectable change). It appeared that, the SDC value of the frequency-related parameter was lower than in the amplitude-related. This suggested that, the frequency-related parameters are in greater agreement than in the amplitude-related one. This also implied the more suitability of the investigation for the intervention, which aims to modify motor control [15]. Furthermore, the EMG variable obtained from within-day was greater in agreement with respect to the one obtained from the between-days, which was revealed through the lower value of the within-day SDC than in the between-day. In addition, in comparison with the value obtained from the sustained muscle contraction tasks, described in the study No 3 in table 1. It appeared that, the SDC of the EMG variables obtained from the repetitive movement task were higher than the ones obtained from the sustained muscle contraction. This indicated: the variables obtained from the repetitive movement task were in poor agreement than the ones obtained from the sustained muscle contraction [15].

5 Conclusion

By researching the applications of multi-channel surface EMG on the assessment of muscle fatigue/activation, it was evidenced that, there had been a huge continuous progress on R&D over related technology and technique since 2005 (this study searching scope 2005 - 2015).

In terms of ergonomic evaluation, this method could have been used potentially for the evaluation of muscle fatigue or muscle activation even during the daily work tasks. Remarkably, the application of multi-channel surface EMG, applying with the newly mathematical algorithms, allowed its ability to reduce the variability of the calculation, which results from the non-uniformity of the muscle activation. Particularly, it is even more efficient when utilizing through the two-dimensional array of electrodes, due to its larger detection coverage property. Furthermore, this newly advanced technique combined with the capability of the spatial muscle distribution monitoring property contribute to the benefit of the monitoring muscle activation across regional muscle areas being investigated. Considerably, these unique features are not capable for conventional bipolar surface EMG to cope with.

6 Limitation

The massive amount of information all across investigated databases, together with the diversity of the presented electrical sensor names, may have led to the loss of some relevant information, which possibly occurred during the search process. In addition, there had been a few studies found related to the EMG applications of multi-channel surface EMG, conducting in the real working condition. Particularly, for the application in the repetitive movement condition, which requires so much sophisticated techniques and specific equipment. By these, it may have implied something about, most of the knowledge in this issue has mainly been conducted through the ideally controlled conditions, set up in the laboratory. Beside, most of included relevant studies in this review, which was focused on related-ergonomics evaluation, were conducted mainly by investigating muscle fatigue on upper limbs. This seemingly suggests that other muscle portions studies such as lower limbs and so on are still needed, in order to obtain the most comprehensive understanding of this fatigue evaluation in Ergonomics, which could probably be utilized in the real-world application soon afterward.

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4 OBJECTIVES AND METHODOLOGY

As the previous states, work-related muscle fatigue has been widely seen and becoming one of the most prevalent symptom, associated to Musculoskeletal Disorders (MSDs). Moreover, it also appeared to be the most prevalent occupational-related health problem in Europe, affecting millions of workers. Considerably, across the EU27 member, 25% of workers complained of backache and 23% reported muscular pains (OSHA_European, 2007). Although, the European agency has been conducting several measures, attempting to prevent and reduce those problems, mainly through a number of relevant legislations and standards. Nevertheless, muscle fatigue involved in work related musculoskeletal disorders (MSDs) has still been reportedly documented in various different occupations (Troiano et al., 2008).

It is widely recognized that the best measure against any source of problem is the preventive ones, in order to avoid the possible occurrence of the problems. On the other hand, if we allow the unwanted incident to happen, it would be too late to secure any safety aspect. From the literature reviews section, the HD-sEMG demonstrates its sophisticated properties in assisting as well as identifying of muscle fatigue signs, particularly its high potential in practical application such as in the real-world working condition.

There had been quite a lot of a conventional bipolar surface EMG application in working environment so far, however with its limited capability, this might not be efficient or accurate enough for the more complex application, particularly involved in a pre-diagnosis content. And with the found HD-sEMG superior potentials prior stated, this had contributed to the core of this research, which could be comprehensively explained its objectives and methodologies in details as following.

4.1 Objectives

This thesis objectives mainly focus on the methods to assess muscle fatigue suffered by workers via the EMG signal analysis. The assessment of the muscle fatigue was conducted in working environment during a regular-work routine. The measurements were conducted on both, healthy subjects that acted like a baseline sample, and subjects with MSDs problems, which were identified by medical diagnosis methods, consisting of shoulder MSDs and elbow & wrist MSDs cases. All related medical diagnosis information was accessed through a permission from the factory authorities and the workers themselves. It was documented via the term of employee medical records history, which the factory had long been implementing regularly since its establishment. All those specific objectives can be detailed point by point as following:

a) The main objectives

To evaluate the development of muscle fatigue, which was considered over workday and throughout the entire weekday, by High-density surface electromyography (HD-sEMG), occurring on upper trapezius during repetitive movement (dynamic contraction) in workers, who were working in a food industrial sector in Portugal (a cheese production factory).

To identify/distinguish workers, who are at risk of work-related MSDs, which could be affecting at different muscle portions, by analysing the development of EMG variables tendency, Namely, all could be analysed by comparing the EMG developing tendency among the different participating medical-diagnosis cases.

To determine the relationship between the objective parameters (EMG variables) and the subjective one (questionnaire surveys of local perceived discomfort) of the fatigue obtained from those workers, whether form the healthy subjects or from the affected MSDs ones.

b) The minor objective

To verify the possibility of applying this type of HD-sEMG in muscle fatigue evaluation, particularly in the clinical-related application, such as its capability to distinguish the different affected-muscle condition in such a real-world working environment.

4.2 Methodology

The methodology of this study was begun with a literature review of the topic under study. This research of the literature review had revealed a number of key findings, consisting a numerous of study-related evidences. Many of them had implied/stated that: HD-sEMG is feasible and reliable for an application involved in determining physiological characteristics of muscle fatigue, whether in static or even during the dynamic tasks. By this, it suggests that: the HD-sEMG is likely to be efficiently capable of applying in the actual real-world working condition such as in the daily working routine.

After obtaining the possible theme of the research, other next relevant processes were consecutively conducted. There are many relevant key points necessary for accomplishing the goal, which could be described in depth consecutively, step by step as following.

4.2.1 Selection of manufacturing, task performing procedures and studied muscle portion

Regarding to conducting the research in the real-world working condition, it could be considered as a quite complicated job compared with the laboratory set up one. This is due to the fact that there could be many factors possibly associated with the good understandable results. Therefore, many conditions need to be carefully taken into accounts, in order to have as high quality of data collection and the most reasonable results as possible.

In addition, the cooperation and authorization from the factory for allowing the research smoothly conducted was also considerably important, otherwise the entire research wouldn’t be properly taken place anyways. Therefore, in order to accomplish all research goals, pretty much information needs to be clearly determined in the first place prior to the data collection, including the selection of manufacturing type, studied working department type and the task performing procedures. All those in depth details could be classified and described as below.

4.2.1.1 Selection of studied manufacturer and production type department

After an intensive study of many regional operating manufacturers, it appeared that, one food industry (Cheese production) was greatly relevant and complied with the topic under study. Namely, there was a high level of intensive manual-handling repetitive movements, as well as the reportedly prevalence of MSDs problem. Regarding to a field survey at the factory during the beginning stage of this research, it was obviously evident that the packaging department was the factory most experiencing manually-repetitive movements.

In addition, it was also corresponding with the factory's medical records history of the employees, which revealed the most affected work-related MSDs workers were reportedly from this department. Therefore, the production line of this department was then selected to be studied exclusively in the first place, in an attempt to process through the next step that is the determination of the most effective production spot (station) for the data recording. This department can be classified its production line processes, based on different tasks of workers (automatic machine processes were not counted in this criteria) into 4 workstations, which could be explained as following (shown in figure 26 and figure 27):

1. Manual products feeding
2. Cleaning & inspection and lining up cheeses on the conveyer belt
3. Box packaging
4. Transporting box packaging onto pallets

Considerably, all workers in this production line were organized to have rotating work tasks, cycling across those 4 different workstations. This measure was established by the factory occupational safety and health affair, intentionally handling against any heavily prolonged repetitive task. In addition, for the workers with the report of work-related MSD effect, they were going to be specially taken care by allowing them to carry out relatively lighter tasks during the second part of the day. Otherwise, they would not be capable of enduring such heavily intensive repetitive task throughout the whole workday as similar to the healthy ones.

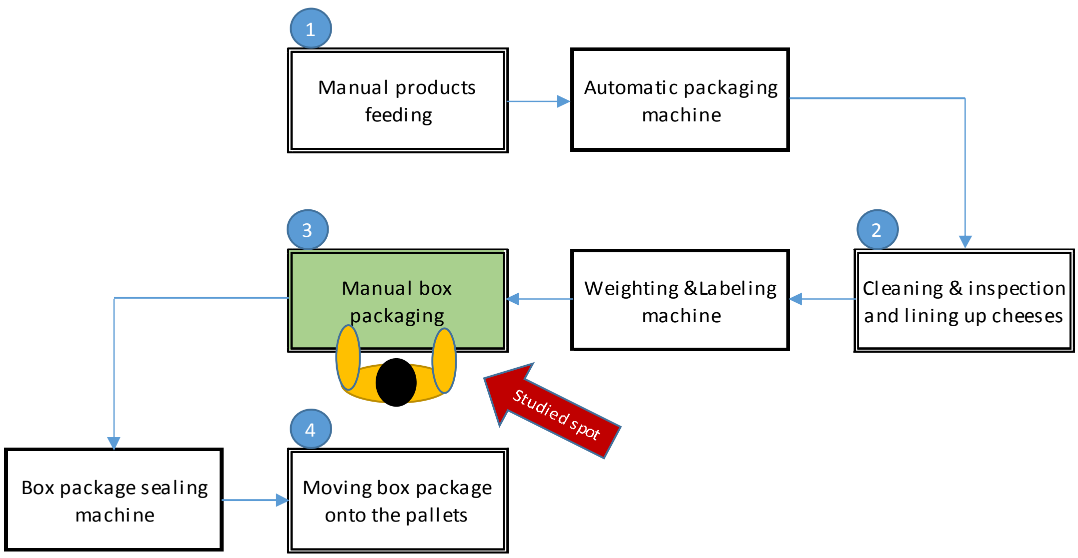

Figure 26. The station layout and flowing task movement of the packing production department.

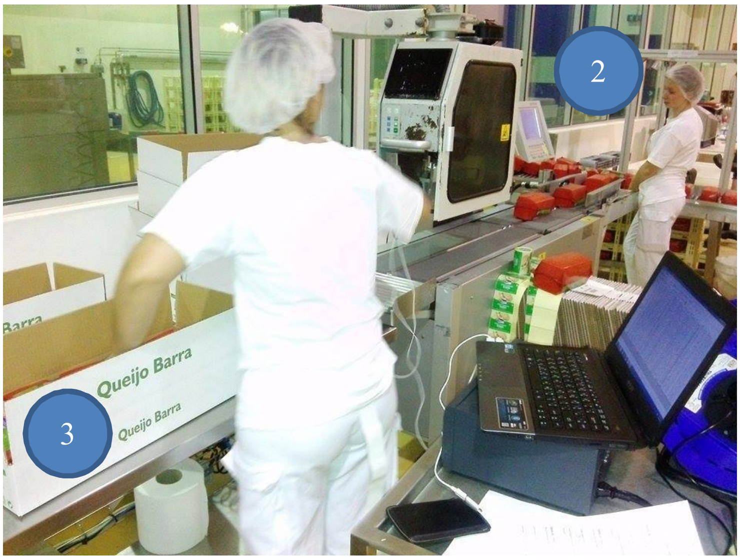

Figure 27. The manual box packing task of the packing production department.

4.2.1.2 Selection of the studied task performing procedures

After carrying a detailed study over all four existing work stations, the manual box packaging station was then selected as a studied spot. Regarding to its advantage over the others, which can most provide key essential requirements of this research data collection including:

- Workers working at this station had to perform the heavily repetitive movements, particularly on their right hands and shoulder.
- It can comply with the technical requirement of the data collection, consisting of an enough space for all necessary equipment and all relevant movements.
- Its friendly surrounding condition for the data collection, regarding to the electronic instruments are not designed for working in such high humid/wet condition.
- At this production process, it could generate less affect over the product quality control in term of a sanitary issue, while still maintaining the objectives of this study.

All voluntary subjects were asked to perform their daily work task of packing cheeses by using their right hand, carrying the products from the moving conveyer belt into the packaged box. All were done cyclically as a loop, which could be described step by step through the demonstration in figure 28.

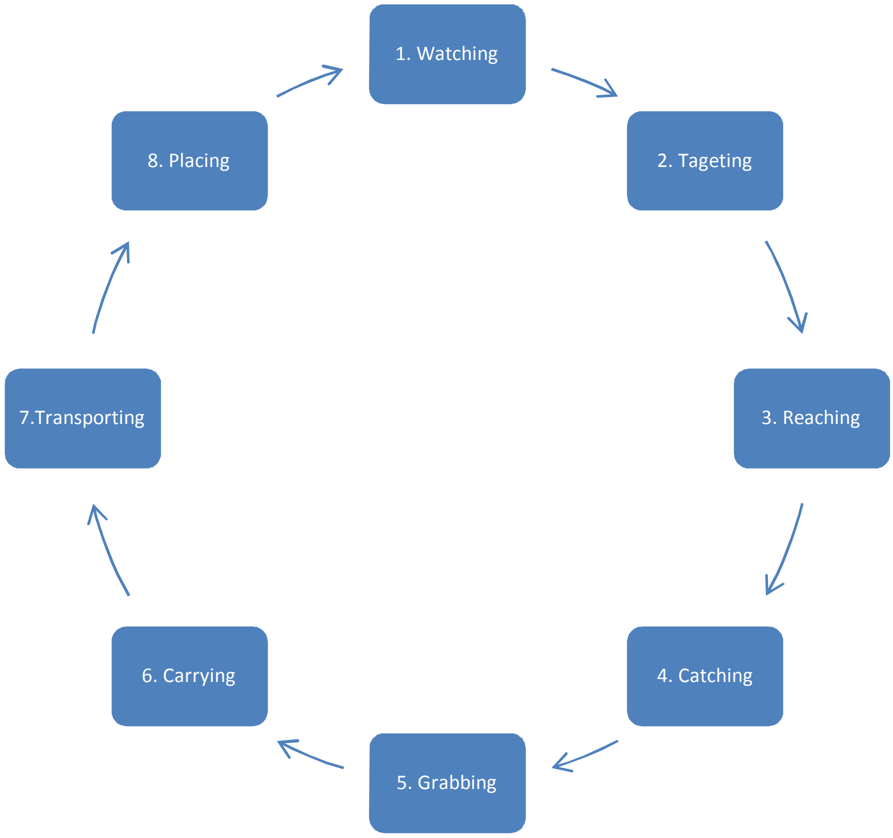

Figure 28. A loop procedure of one cheese placement on the box packaging process.

In addition, these workers also performed once again the quality control through their visual inspection during the packing task, despite this inspection had already been performed on the previous work station No 2. By these, it could be considered as a monotonous, high-intensity task, and heavily dynamic repetitive arm lifting and transporting with loaded products.

In fact, this box packaging work station did not only perform just containing cheese products into the box, but the workers also needed to carry out other processes through the entire work task. It was all done cyclically as a loop, which can be demonstrated step by step as in figure 29.

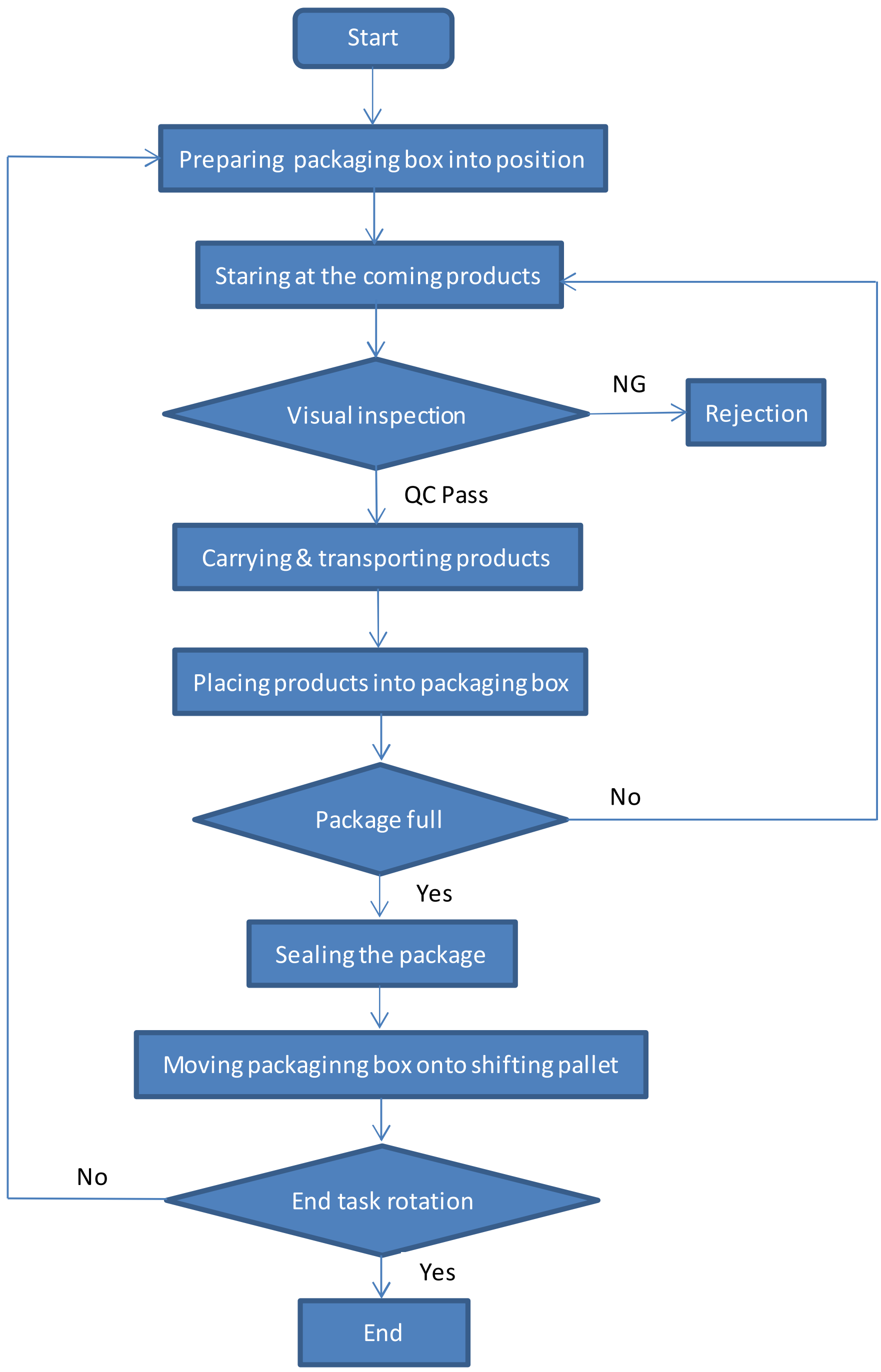

Figure 29. The entire task procedure of a studied spot on the box packaging process.

During the task performing, the cheeses box packaging rate was paced by the moving conveyor speed, with an approximate rate at about 1 piece per 2 second at the peak, but it appeared not to be that continually over the 5 min of recording period. In reality, it was likely based on the synchronization between a box packing loop and a feeding rate, which was determined by the work task No.2 (Cleaning & inspection and lining up cheese on the conveyer belt). Seemingly, it is an intention to prevent a bottleneck situation of the cheese being in packaging process.

The production intensity was dominated by a daily production target, given by the production planner department. All workers were organized to have tasks rotation across the whole 4 workstations as shown in figure 26, which is designed to prevent the heavily prolonged repetitive movement. The workers were allowed to have a reasonable micro-break during the day, and a major break for 30 minute at the middle of workday. They had to work for 8 hrs a day and 5 days a week in general, affecting for all 3 work shifts. The studied work shift period was a 13:00 – 21:00 work shift, with 30 min break at 16:30 – 17:00 hr. The demonstration of work task and feeding conveyor belt can be shown in figure 30.

Figure 30. The work task of cheeses box packaging station.

4.2.1.3 Selection of studied muscle portion for HD-sEMG employment

According to 4.2.1.2, the manual box packaging station was selected as the studied spot, according to all advantageous evidences as already described above. It was noticeable that with the particular required task movement, shoulder and arms were likely to be the major portions of accomplishing this task performing that demanded a very heavily repetitive movement. However, if considering much deeper in a physiology detail, an upper trapezius was playing a key role behind those movements. In accompany with other evidences, the upper trapezius portion seemed to become the most popular selected muscle portion in this relevant research field, for example: (Madeleine et al., 2006b, Laura A.C. Kallenberg et al., 2007, A. et al., 2008, Deborah Falla et al., 2008, D et al., 2008, Deborah Falla et al., 2010, Barbero et al., 2011). This might be due to its location that pretty both most easily accessible and suitable for the HD-sEMG arrays electrode employment.

In addition, there is another involved study, conducted by Falla and colleagues (Falla et al., 2007b). They set up the experiment investigating changes in spatial muscle activation over three different trapezius muscle divisions, including: upper division (assessed by three consecutive 5 × 1 array electrodes), middle division (assessed by two consecutive 5 × 1 array electrodes) and lower division (assessed by three consecutive 5 × 1 array electrodes). All were done during the repetitive dynamic task. They found that the amplitude-related parameter had a significant effect on upper and middle division of trapezius, while the frequency-related parameter had a significant effect on upper and lower division of the trapezius. Evidently, both results obviously suggest the upper trapezius, which can be shown in figure 31, is the most effective and sensitive portion for the EMG fatigue estimation over the shoulder, due to its most effective combination of both amplitude and frequency related parameters.

After all, to be more trustable, it would be more advantageous on a benefit of comparing this study result with those results, since they are conducted on the same muscle portion.

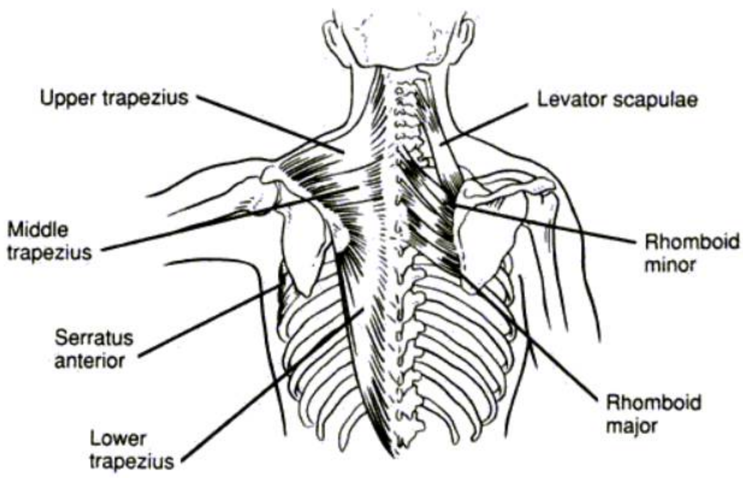

Figure 31. Physiology diagram of trapezius muscle (Davis et al., 2000).

4.2.2 Subjects

In this selected food industry (cheese production), all participants were from workers who were working at this studied packaging department, which required heavily manual handlings on the packing procedure. All those were female consisting of twenty voluntary workers (age: 29.8 ± 8.85 years, height: 160.45 ± 5.62 cm, weight: 64.80 ± 14.57 kg, BMI: 25.05 ± 4.68 kg/m^2). All of them were provided informed consents and returned back to the research team prior to the starting of the research study (data collection).

4.2.3 Shoulder and arm medical examination methods

According to the employee historic medical record, accessed with authorization from the workplace's occupational health and safety authority, there were three recorded medical diagnosis methods available on shoulder, elbow and wrist. They had been previously examined according to the employee health care monitoring measure, which consisted of: symptom, medical examination and scan (echography).

The medical recording indicated that, five subjects were suffering with shoulder MSDs. They were diagnosed from the occurrence of whether symptom, medical examination or scan (echography) method (due to the shoulder was a major portion of this study, where surface EMG arrays electrode was employed, therefore whichever appearing result over the three different methods, it will anyways be considered). For without shoulder MSDs problem cases, other two subjects were suffering with elbow & wrist MSDs. It was determined from the combination of at least two existing diagnosis methods from those three different ones (due to no EMG measurements on these portions, so the degree of interest is considered less than the case of shoulder MSDs). There were no subjects with a single MSDs problem on either wrist or elbow portion. The rest of other thirteen subjects, who were out of this diagnosis criteria were considered healthy on shoulder and arms.

4.2.4 Surface EMG recordings

Surface EMG signals were detected with semi disposable adhesive matrix 64 electrodes, 13 rows and 5 columns (3 mm diameter, with 8 mm inter-electrode distance), model ELSCH064NM2 with one electrode absent at the upper right corner as shown in figure 32. The detected raw EMG signals were then amplified by EMG-USB2 multichannel bioelectrical signal amplifier with 144 channels, LISiN-OTBioelettronica, Torino, Italy, Bandwidth 10-500 Hz, with equivalent input noise less than 4 μV_{RMS}, CMRR >95dB. The amplification was done by a factor of 5000, at the sampling frequency of 2048 Hz, before being later converted into a digital form via a 12 bit A/D converter. For a ground electrode, it was placed around the right wrist of subject, as shown in figure 33.

The electrode montage recording configuration was set as monopolar, regarding to its properties, which is considered as most suitable for detecting the EMG signals. Regarding to its advantageous properties which are able to provide the most precise none-distorted signals, and remarkably detectable from deeper muscle fibres with respect to the bi-polar one, as previously explained comprehensively on section 2.3.3.3 (Electrode montage recording configuration).

Subjects were placed the semi disposable adhesive matrix 64 electrodes on their right hand over the upper trapezius muscle as shown in figure 34 and 36. This was according to a layout of the designed production line, forcing workers to use their right hand in performing the tasks. All electrode placement procedures were conducted complying with SENIAM recommendation. The sensor placement location was determined at the centre of the line, drawn by water prove marker between 2 anatomical points of the acromion and vertebra C7 spine as shown in figure 34.

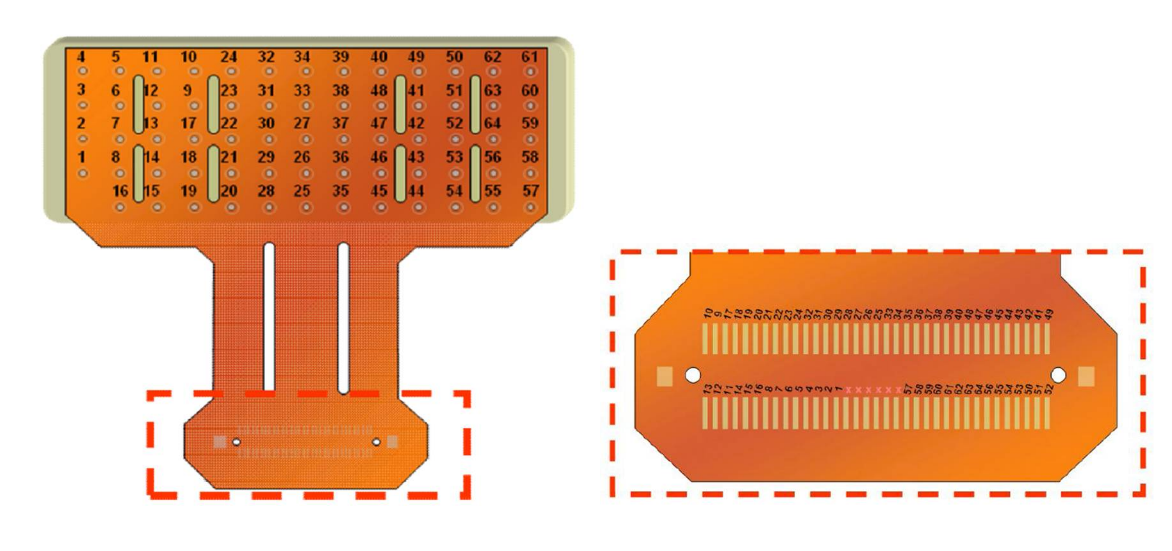

Figure 32. Adhesive matrix model ELSCH064NM2 Pin Out (Bioelettronica)

However, prior to the electrode placement, subjects' focused skin area needed to be prepared properly. This is according to an attempt to obtain as most efficient data recording as possible, which includes whether: a good electrode-skin contact, better surface EMG-recordings (in terms of amplitude characteristics), lower/smaller artefacts generated (electrical interference), less risk of imbalance between electrodes (smaller common mode disturbance signal) and less noise (better S/N ratio) (SENIAM).

The skin preparation processes started from observing subject's skin at the marked point, if it was covered with excessive hair, it may have to be shaved before the attachment, in order to ensure a strong bond of sensor interface and better electrode contact with the skin. But if it was covered with acceptably pretty less hair, this particular skin area was considerably not necessary to be shaved. After having the proper skin prepared already, then applied alcohol onto the previous marked area, cleaning and allowing it to be completely vaporizing, so that the skin could be drying out and ready for the next steps. Sequentially, started applying the conductive and abrasive paste which is especially made for reducing the skin impedance during the EMG measurement.

For the electrodes preparation, each electrode array was attached with the specifically designed 64 adhesives array, exclusively made from the same electrode producing manufacture. After that filled each cavity of the set of electrode and adhesive array with conductive gel, which is designed on the purpose of increasing the electrical conductivity during the measurement, as shown the process in figure 35.

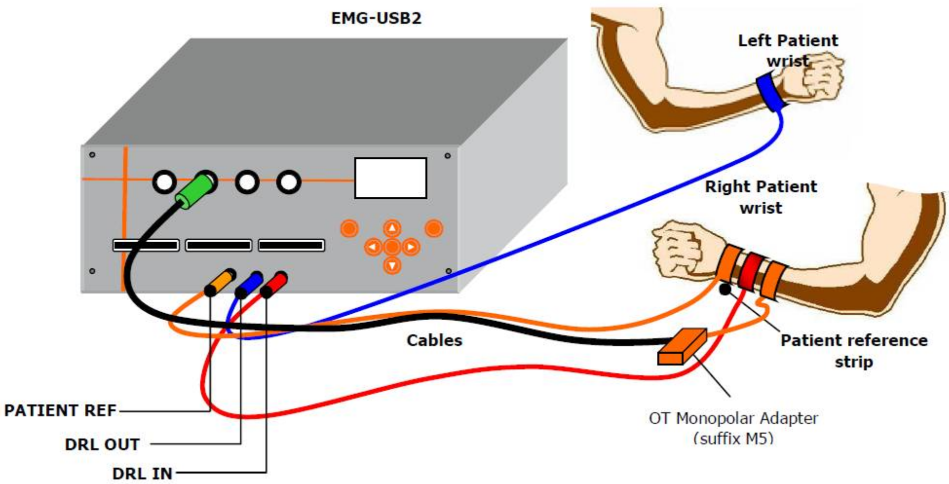

Figure 33. The connection of EMG-USB2 multichannel bioelectrical signal amplifier with 144 channels, (LISiN-OTBioelettronica, 2015) .

The electrode array placement was accomplished by placing it onto the prepared skin, with the centre of electrode array located right at the spot of the previous marked skin position. Once having the electrodes placement completed, secured it once again by using an adhesive tape. This process aimed at ensuring the attachment to be as much secured as possible as shown in figure 36. The electrode array must not be losing from its position during the long whole day data recording, otherwise the obtained signals would be contained with a lot of noise. Moreover, in the worst case, the entire information of expected EMG signals might be lost if the electrode array totally loses its attachment with the skin.

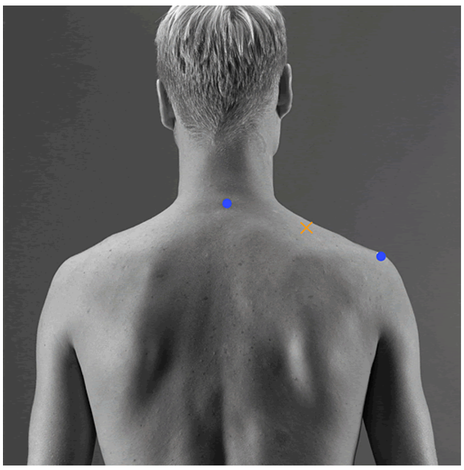

Figure 34. The marked location and its alignment for surface EMG arrays electrode placement (marked between 2 anatomical points of the acromion and vertebra C7 spine) (SENIAM)

Prior to the recording tasks, subjects were asked to perform the standard isometric test contraction, with arms held abducted 90° at the shoulder high for 30 sec (Suurkula J. and Hagg G.M., 1987, Bosch et al., 2007) as shown in figure 37. This carrying out was designed for their reference value that is going to be normalizing with other individual EMG signals obtained from each task. This is regarding to, with this position, it induces the load on upper trapezius by about 15 – 20% of the maximum voluntary contraction (Falla et al., 2008, Mathiassen et al., 1995).

The main reason behind the utilization of this standard isometric test contraction, with arms held abducted 90° at the shoulder high for 30 sec, rather than the use of the maximum voluntary contraction (MVC) is due to the difficulty of suffering MSDs subjects, which may not be able to conduct the MVC as normally as the healthy ones, seemingly due to a result of the existing pain they might be experiencing. This effect may lead to an abnormally low value of force obtained from MVC of MSDs cases compared with the healthy ones, which will be eventually affecting the normalization of the final results afterward. In addition, the MVC test prior to the experiment may contribute to muscle exhaustion, happening just before the experiment of the first session data collection, which would be potentially affecting the expected results.

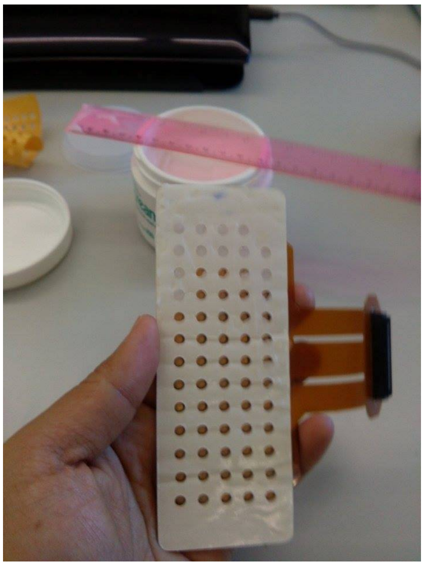

Figure 35. The surface EMG adhesives preparation during the step of filling each cavity of 64 arrays electrode with conductive gel.

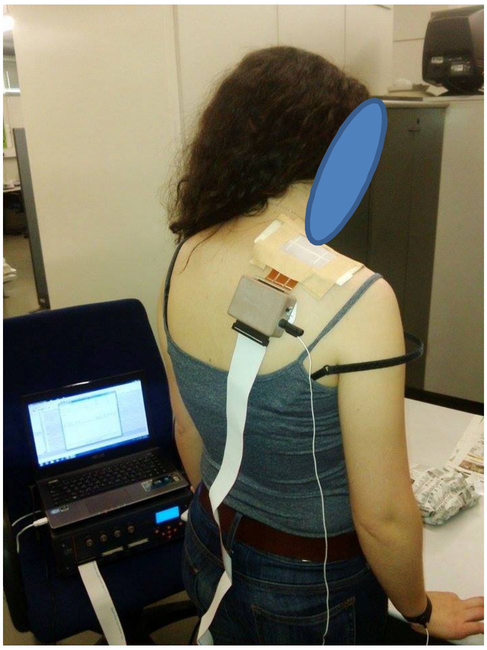

Figure 36. The location of surface EMG arrays electrode placement and its attachment.

The surface EMG task recordings were performed on the work shift of 1:00 – 9:00 p.m., with 30 min break at 16:30 – 17:00 hr. They were conducted over 5 minutes per session, 4 times a day for each subject. The 1st session was measured during the time period around 1:00 – 1:05 p.m., the 2nd was performed for 5 minutes just before a midday break time, approximately during the time period around 4:55 - 5:00 p.m., the 3rd was performed for 5 minutes just after resuming from the break, approximately during the time period around 5:30 – 5:35 p.m., and the 4th was performed for 5 minutes at the time approaching to the end of the workday, approximately during the time period around 7:25 - 7:30 p.m. (there is a limitation of collecting data right at the ending time of the workday).

For local perceived discomfort ratings assessing over the shoulder and neck, it was performed just after finishing each of those 4 task measurement sessions. By this way, it allows the research team to assess the local perceived discomfort (subjective parameter) in comparison with the results from EMG signal (Objective parameter) over several different consecutive times and healthy condition cases. The schematic diagram of all measurement sessions are demonstrated below in figure 38.

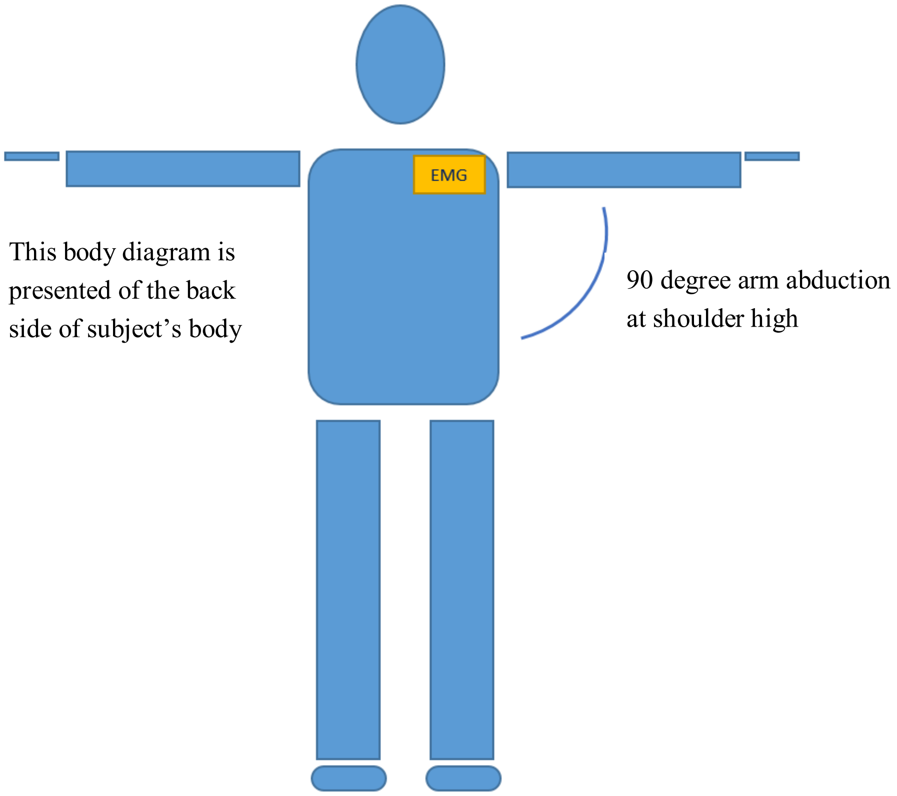

Figure 37. A standard isometric test contraction performing, with arms held abducted 90° at the shoulder high for 30 sec.

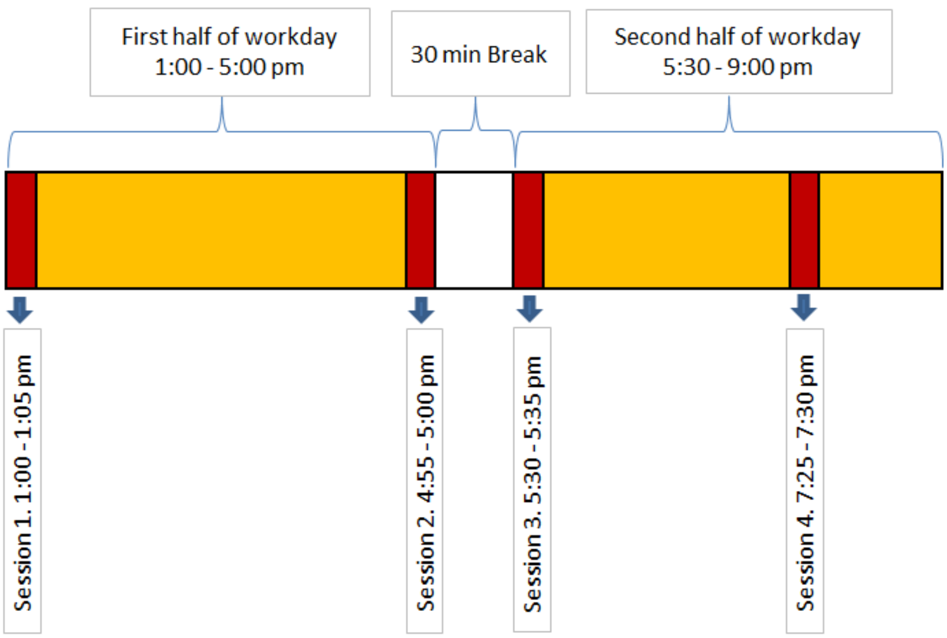

Figure 38. The data collection sessions and the whole workday timetable.

4.2.5 Signal analysis

After finishing all field data collection, the recorded surface EMG signals were afterward digitally off-line band-pass filtered with 2nd order Butterworth filter; -3 dB bandwidth, 10 to 500 Hz. For having some idea of filtering, an example of the filtered result can be generally demonstrated in figure 39. This bandwidth was designated by the knowledge that: the frequency of all active muscles, detected through the surface EMG signals basically ranges only between 10 – 500 Hz (SENIAM).

Therefore, the frequency only between 10 – 500 Hz was then taken in to account (for the other frequency ranges will be considered unrelated as noise). The concept of the filtering is the Butterworth filter that was first introduced by Stephen Butterworth an engineer and physicist in 1930. It then becomes a fundamental theory in signal processing filtering analysis, designing for filtering the noisy signals, to become as flattest (less ripple) frequency response as possible, over the designated bandpass.

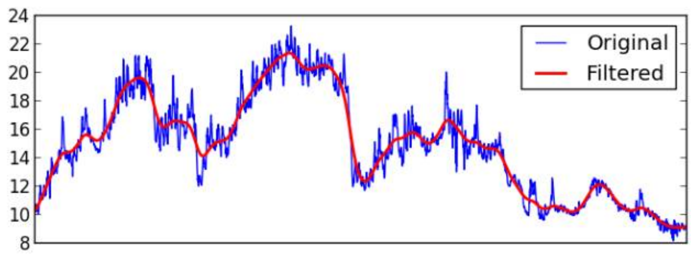

Figure 39. An example of an original and filtered signal processed via the Butterworth filter on one general signal, picture modified from (oceanpython.org, 2013) .

The Root mean square (RMS) and Median frequency of power spectral (MDF) values were computed from each mono polar electrode, recorded from all across 64 electrodes array. This multiple channels calculation is capable of covering a larger muscle area being investigated, which can beneficially provide more information of muscle EMG activity than the conventional bi-polar one. Moreover, this signals calculation was conducted cooperating along with a relatively long epoch of signals, involved in the data treatment. This long epoch calculation is considerably beneficial to reducing the fluctuation of the estimated results, which is significant for minimizing a variance of the estimation (Troiano et al., 2008). This is much essentially suitable for this research that was performed in the real working environment which is likely impossible to control every movement as in the laboratory experimental set up (normally with a simple cyclic movement).

After removing the noise from raw data via the filter process, the reference RMS value obtained from the standard isometric test contraction, performing at the beginning of workday was calculated over all 30 sec of the recording. However, to be obtaining as most detail as possible, it was extracted into consecutive 250ms window for sub-calculating of the RMS value, which was entirely accomplished throughout 30s of the recorded data for each electrode. The final reference RMS value was obtained from the average of each electrode all across the 64 electrode array, which could be explained diagrammatically as in picture 40.

The dynamic task RMS estimation was divided its calculation covering over each 60s across the 5min (300s) recording. This is due to the characteristic of working in a real world industrial site which could not control a source of movement pattern as ideally as in the set up laboratory one. Besides, the data collection main instrument used in this study was only the EMG recording equipment. No other supporting equipment such as video recording device or the angle measuring one, which are significantly necessary in enhancing an accuracy of the signal estimation. Rather than randomly determine the calculated epoch, those supporting equipment could provide the exact instantaneous movement and angle for the designated estimation epoch, giving the most similar movement spot and less outliers of the result as possible, which could reduce the fluctuation in the estimation. In addition, one of these research objectives was to put its practical capability into the test of applying in the real worksite solely.

Each 60s recorded raw data was split into a consecutive 200ms window. This is for a sub-calculating of the RMS value over each window before being normalized by the reference RMS, obtained from the standard isometric test contraction (figure 40). The normalization is necessary for the RMS evaluation, regarding to the EMG parameter could vary largely within the different individual. The calculation will be conducted and averaged all over 60 seconds of each electrode before averaging all 64 electrodes into a final value at last. The entire calculating steps can be demonstrated via the calculating diagram and the graphical signal in figure 41 and figure 42 respectively.

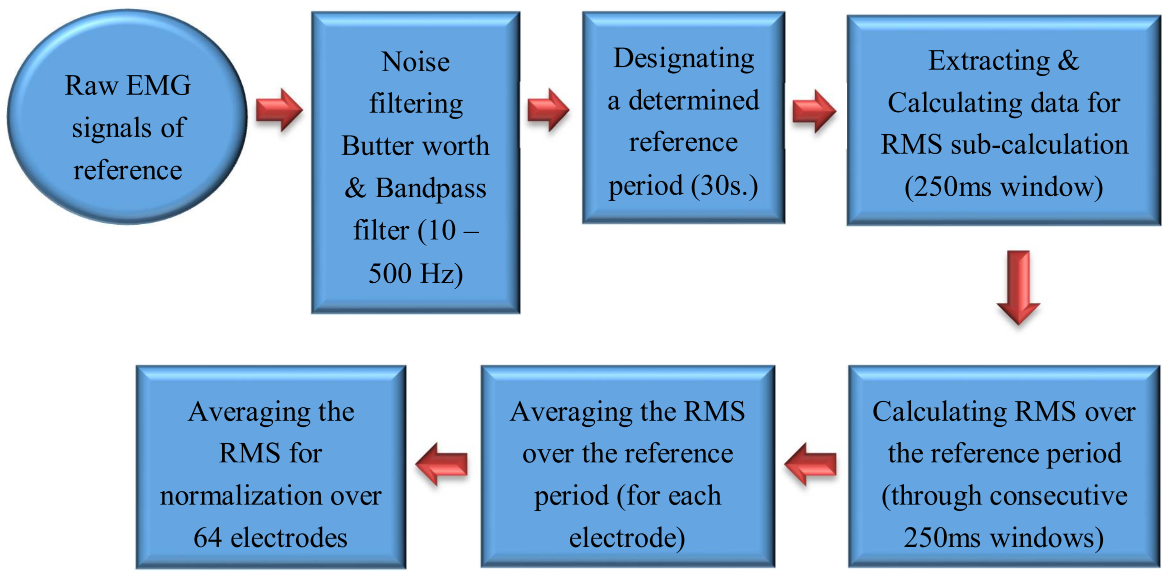

Figure 40. Procedure of reference RMS calculation for normalization process

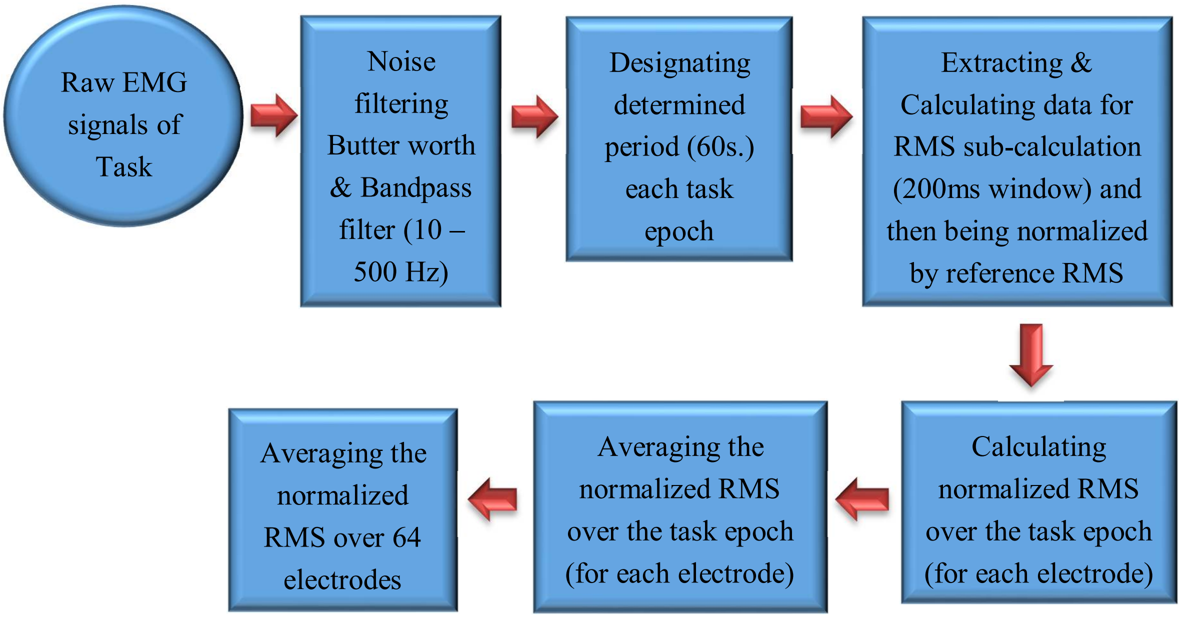

Figure 41. Procedure of task RMS calculation normalized by the reference RMS.

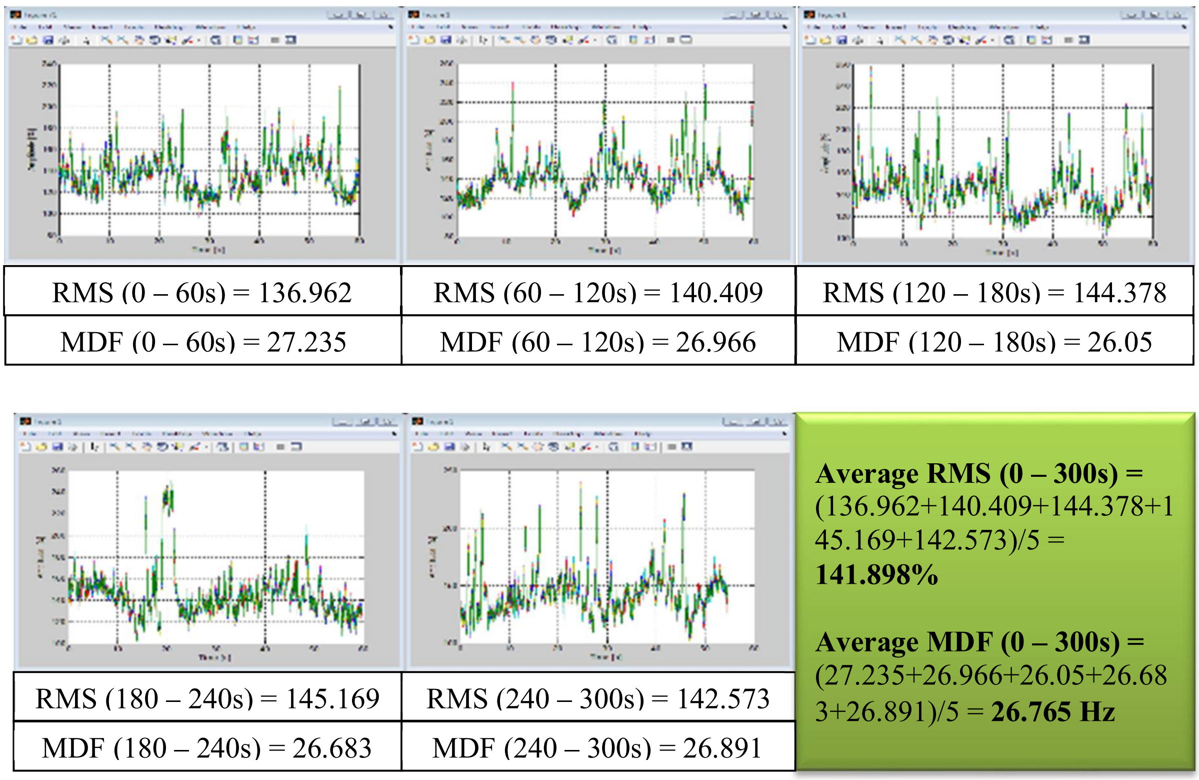

Figure 42. The calculation procedure of RMS and MDF values of 5 epochs with 60s each and their average for a recorded task session.

The Median frequency of power spectral (MDF) value was also calculated over each consecutive designed 60 sec as the same way of the RMS one. However, it was extracted data for sub-calculation epoch via the window of 500 samples (Hamming window) with 50% overlapping with each other (Fs = 2000 Hz; 1 sample → 0.5ms; 500 sample = 250ms plus with 50% overlapping). These split and overlapped windows were designed to obtain as much smoothness of an output frequency spectrum as possible, as well as an avoiding of spectral leakages or outliers of the results.

The Power Spectral Distribution (PSD) was then calculated over each Hamming windows, before estimating the MDF across each of the obtained PSD. This process was performed for all over of each consecutive 60s period of each electrode, and then averaging all results across 300s into one final value afterward. The final MDF value was obtained through an averaging of the MDF value across all 64 electrodes, which could be described in figure 42, 43 and 44.

From figure 44, it demonstrates muscle fatigue quantification on myoelectric spectral analysis during the dynamic contraction. The analysis procedures consist of many consecutive steps: (a) raw data; (b) extracted data, using window sequence (Hamming window); (c), (d) and (e) calculations of MDF over each window sequence with 50% overlapping; (f), (g), (h) demonstrating details from calculating PSD over each window, smoothing the signals and estimating the MDF overreach overlapping window; (i) demonstrating calculated MDF tendency over time of the determined period. Modified from (Cifrek et al., 2009).

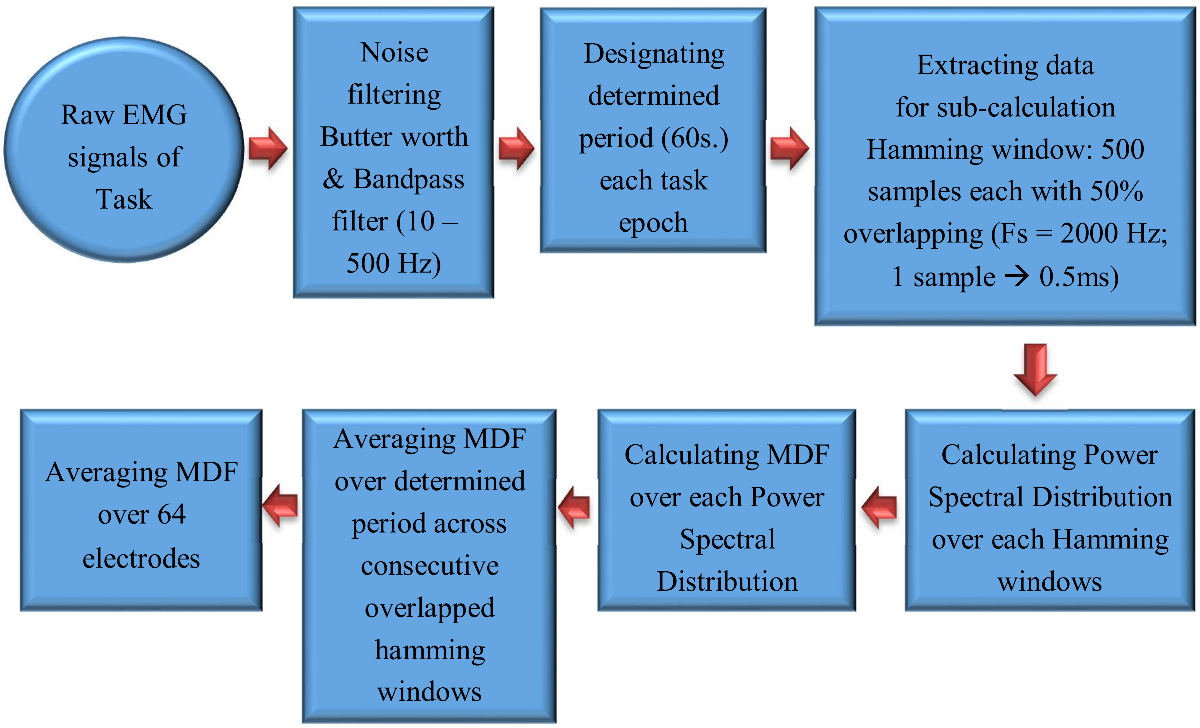

Figure 43. Procedure of task MDF calculation.

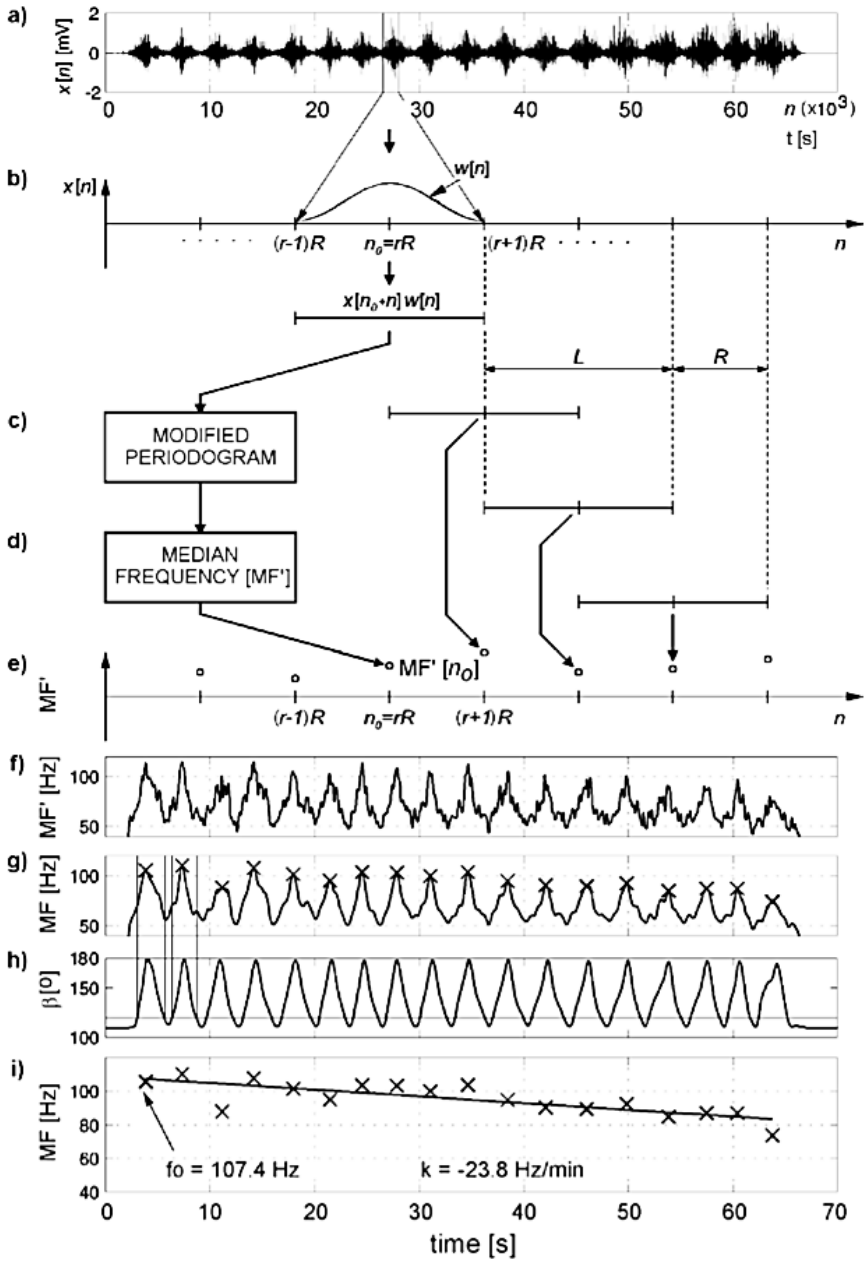

Figure 44. Muscle fatigue quantification on myoelectric spectral analysis during dynamic contraction. All were modified from (Cifrek et al., 2009).

4.2.6 Local perceived discomfort over shoulder and neck

The local perceived discomfort over shoulder and neck investigation was conducted through questionnaires. The questionnaire survey was distributed to all subjects, aiming to investigate level of psychological aspects (local subjective fatigue), experienced by workers while performing their work tasks, which could be accomplished through the local perceived discomfort method (Van der Grinten, 1991).

Subjects were asked to rate the discomfort levels, which were presented on a human body map, by giving the level of discomfort perception through four regions of neck and shoulder: R, P, T, S as shown in figure 45. The discomfort levels were identified on 10 point-scale, ranging gradually from “0 = no discomfort” till “10 = extreme discomfort”, which could be demonstrated the scales of all scores in table 1. The highest discomfort score obtained over the entire four regions was presumably defined as the considered discomfort one, which is going to be taken into account. The ratings were performed 4 times a day, by synchronizing with all 4 task sessions of the EMG recording, namely at the end of each task sessions.

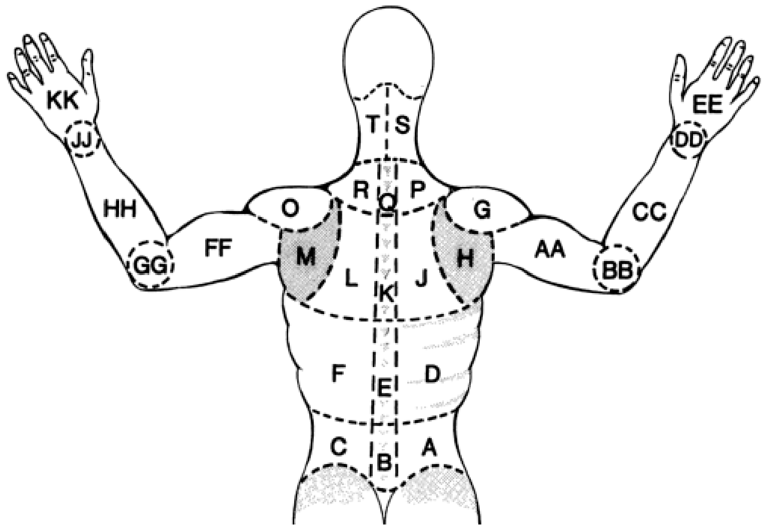

Figure 45. Local perceived discomfort method body-diagram (Van der Grinten, 1991).

Table 1. The score of perceived discomfort method and its relationship with Borg scale and the percentage of the maximum holding time (%MHT).

Discomfort score	% MHT	REC
0 Nothing at all	0	100%
1 Very weak (just noticeable)	10	90%
2 Weak (light)	20	80%
3 Moderate	30	70%
4 Somewhat strong	40	60%
5 Strong (heavy)	50	50%
6	60	40%
7 Very strong	70	30%
8	80	20%
9	90	10%
10 Extremely strong	100	0%

4.2.7 Statistical analysis

Three-way ANOVA was applied in determining the correlation among the investigated parameters which mainly consist of dependent variables and the independent ones. The dependent variables consist of RMS, MDF and the local perceived discomfort over the shoulder and neck. All three dependent variables were going to be determined the relationship with three different groups of independent variables, consisting of [Medical diagnosis; (Healthy, Shoulder MSDs, Elbow & Wrist MSDs)], [Task; (task1, task2, task3, task4)] and [week-day; (Mon - Wed, Thu - Fri)] as repeated measures.

Giving the easier-understanding supporting view, the schematic diagram of this statistical analysis was demonstrated in figure 46. The significant differences revealed by ANOVA were later taken toward the following step of a post-hoc test that used Fisher's least significant difference (LSD) pair wise comparisons. Regarding to this post-hoc comparison principle, it is fundamentally designed for the comparison of the mean value of one group with the mean of another. By this, on the other hand, it could have been stated that: the Fishers (LSD) test is basically a set of individual t-tests (Green, 1997). Meanwhile, the other often found statistics options, for example the Student-Newman-Keuls (SNK) or Tukey's Honesesty Significant Difference (HSD), all apparently do require the matched sample size of all groups being in the process of the comparison (Noakes, 2000).

For these reasons, the Fishers (LSD) test obviously became the most matched statistics option for this research study. This is due to the elbow & wrist MSDs case went missing during the (Thu – Fri) week-day, which was due to the absence of subjects, leaving the unequal size of the sample groups among the week-day (Beginning week-day: 3, Ending week-day: 2).

By this way, the healthy case in this research could be utilized as a reference standard over the shoulder MSDs and Elbow & Wrist MSDs samples. By the way, the statistical significance was accepted at $P < 0.05$, and all results were demonstrated in their mean value.

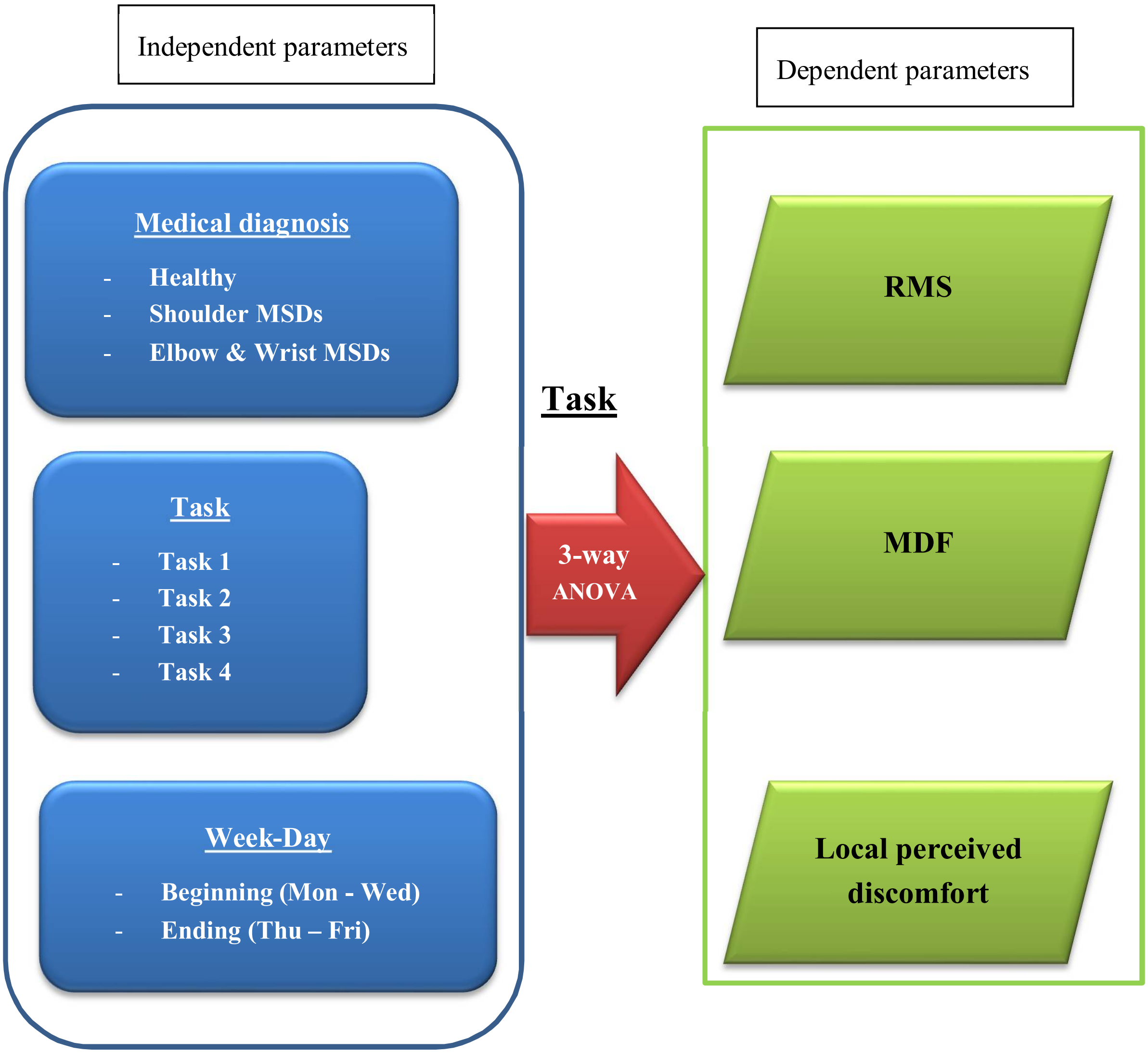

Figure 46. Schematic diagram of 3-way ANOVA statistical analysis.

5 MATLAB PROGRAMMING

As previously explained all the technical details of signal analysis on the section 4.2.5. In this chapter, it will be devoted for the explanation of all operating source code, responsible for the entire calculations of all parameters involved in this thesis research. The software that was utilized in all signal calculations was MATLAB 2013a (MathWorks Inc, USA). And certainly, all the involved programming was operated by MATLAB code.

By the way, the contents in this section will be explained via program flowcharts over all calculation steps, regarding to it property of providing a consecutive step by step of the complex calculation. Expectedly, they could provide all readers the overall figure of the programming. For readers who are interested in MATLAB code programming, it is advised to study more detail in the appendix section at the end of this report.

5.1 Program flowchart

All operating MATLAB codes were designed to be working following the flowcharts, which are going to be presented in the details below. However, they were not originally designed for a fully automatic calculation of all studied variables together at once. Therefore, there were some processes still needed to proceed manually. Namely, each studied EMG valuable, which consist of RMS and MDF, is going to be calculated variable by variable individually.

The program flowchart content was divided into two main subsections which will be operating sequentially in the running process: 5.1.1) flowchart diagram of normalization M-file and then followed by subsection 5.1.2) flowchart diagram of dynamic-task session M-file. All can be explained in detail as following.

5.1.1 Flowchart diagram of a Normalization M-file

Before getting deeper into full details of its flowchart diagram, it is necessary to know the specific information of any involving parameter, which needed to be designated into the programing. The entire steps of the normalization can be explained briefly in term of technical software processing as following: Before starting the workday, all subjects have to perform a standard isometric test contraction for 30 sec., acting as a reference value over all task sessions, which were conducted 4 times throughout the workday. These EMG signals were later off-line band-pass filtered (2nd order Butterworth filter; -3 dB bandwidth, 10 to 500 Hz), then calculating RMS parameter across an entire recorded 30 sec period with 250ms window of sub-calculation. Afterward, this value will later be used in normalizing over each recorded dynamic-task session, which is going to be demonstrated in section 5.1.2. In this case, it was presented in three consecutive steps consisting of:

a) File loading section

b) Preparing data to be ready for next steps calculation

c) Calculating averaged RMS value for each electrode

5.1.1) Flowchart diagram of Normalization M-file

5.1.1 a) File loading section

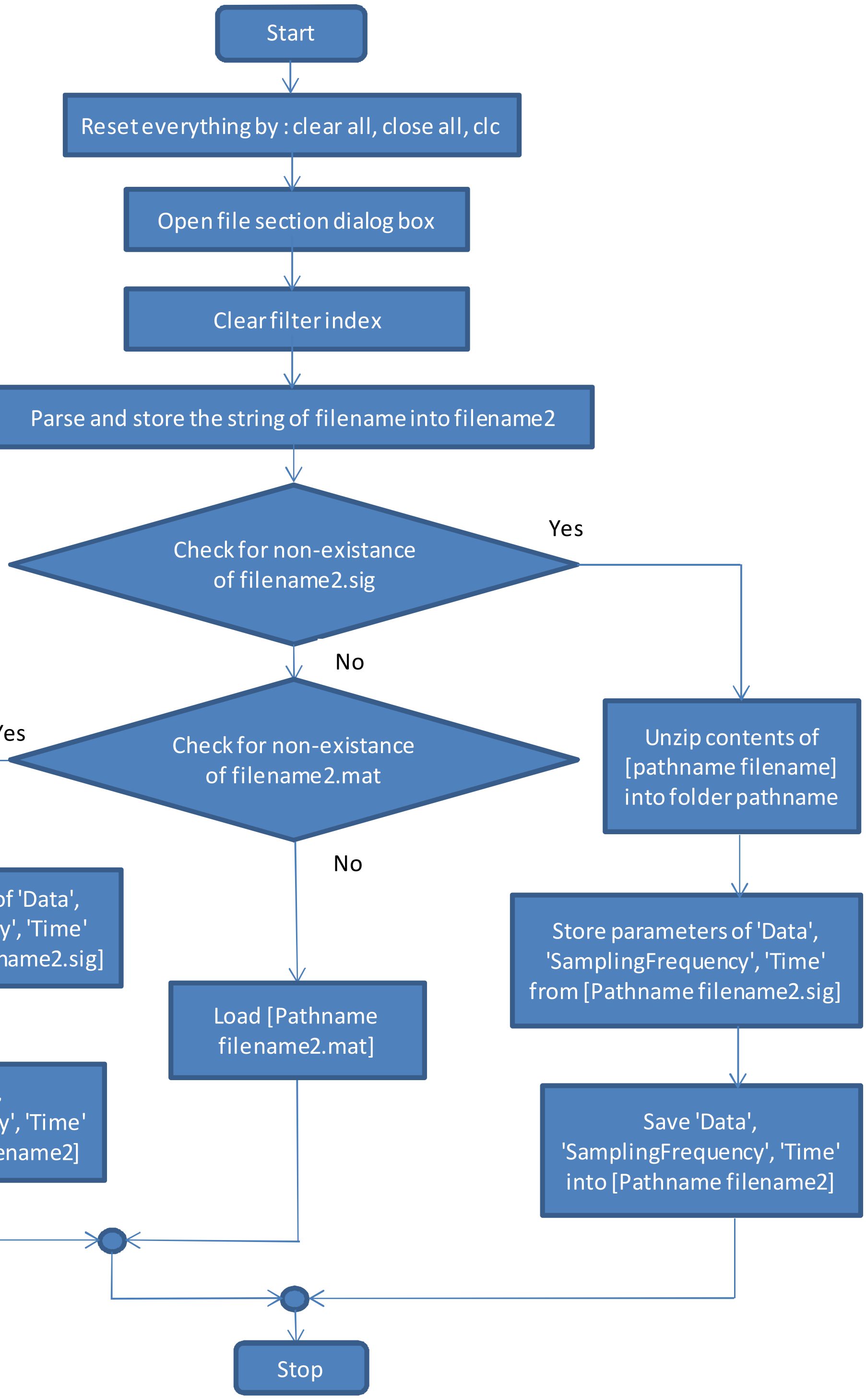

Figure 47. Flowchart diagram of normalization M-file for file loading section.

5.1.1 b) Preparing data to be ready for next steps calculation

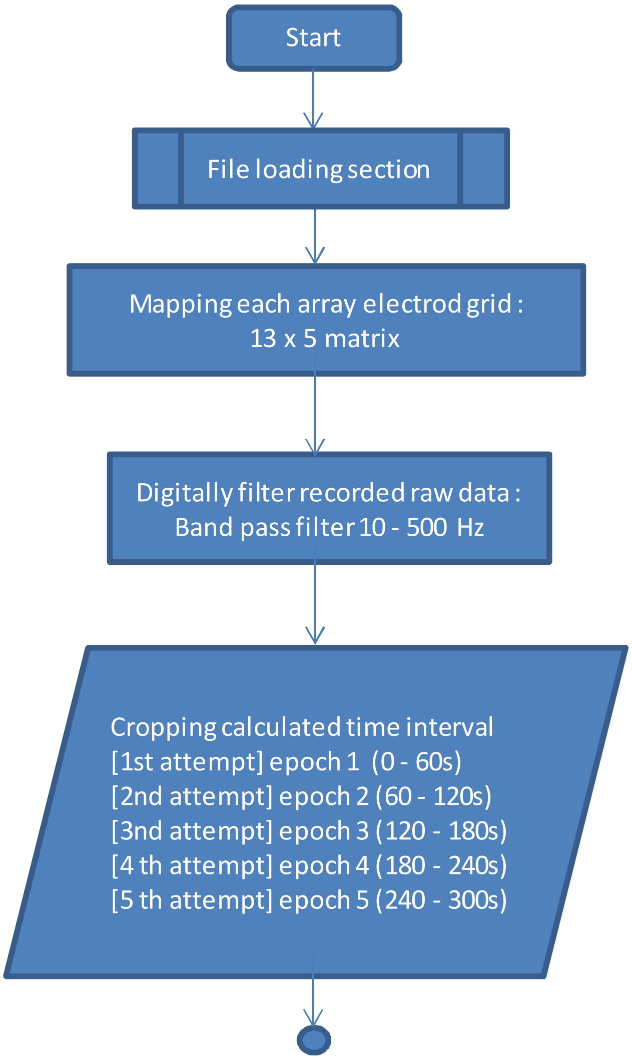

Figure 48. Flowchart diagram of normalization M-file for preparing data ready for next step calculation.

5.1.1 c) Calculating averaged RMS value for each electrode

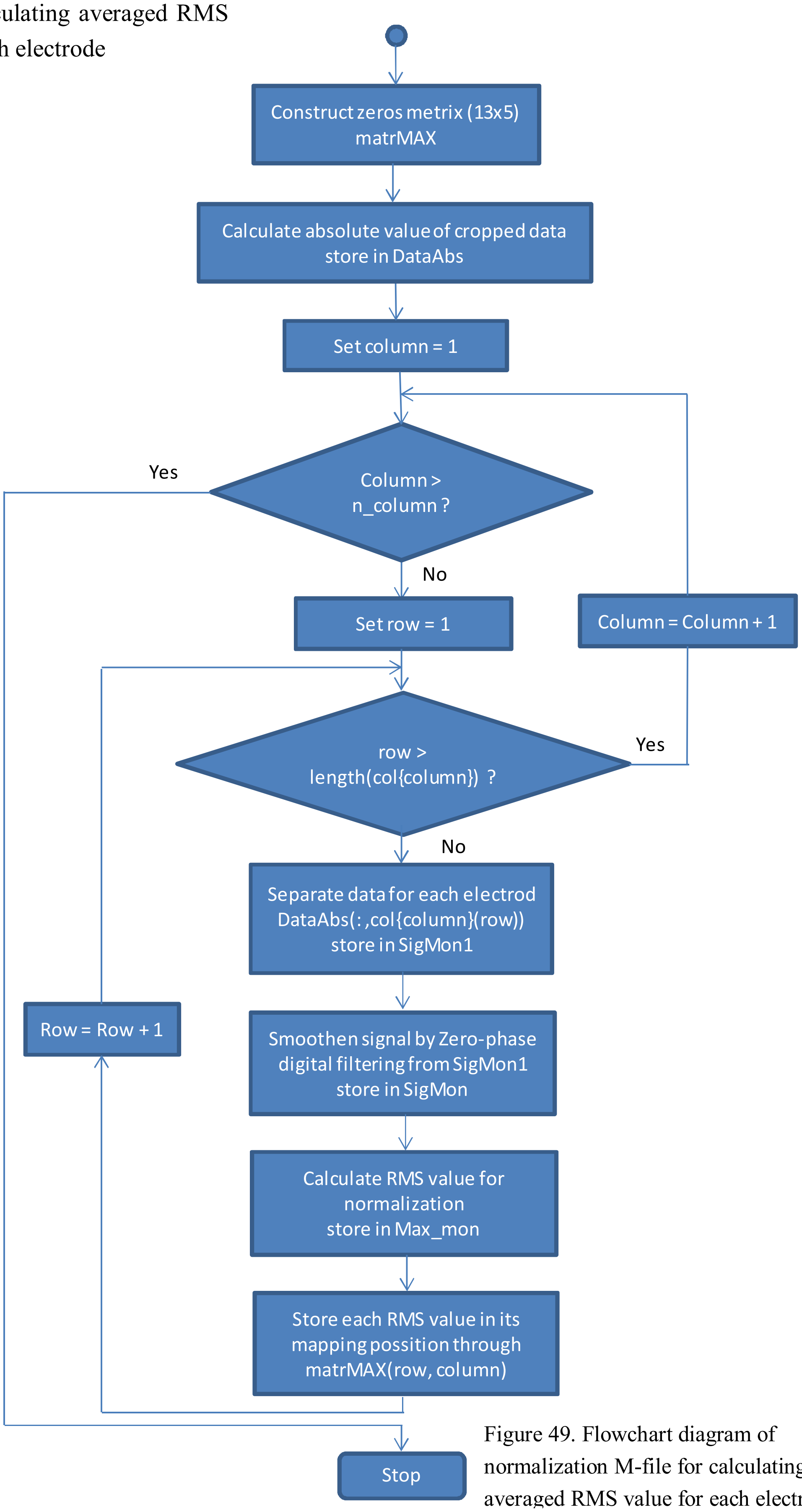

Figure 49. Flowchart diagram of normalization M-file for calculating averaged RMS value for each electrode

5.1.2 Flowchart diagram of Dynamic-task session M-file

In this section, it was purposed to explain all steps of MATLAB programing via flowchart diagrams of all dynamic-task sessions. This part was mainly divided into two different subsections, following the expected output of EMG variables. The flowchart diagram of an averaged RMS calculation and averaged MDF were presented respectively. Accompanying with those flowchart diagrams, all major processes as well as the specific involved information, which are necessary for declaring into the programming, were also described briefly in technical details, as clearly demonstrated as following.

5.1.2.1 The averaged RMS value calculation

The raw surface EMG signals of every dynamic-task session was cropped consecutively over every 60 sec across the entire 300 sec of each recorded session period. Then it was off-line band-pass filtered (2nd order Butterworth filter; -3 dB bandwidth, 10 to 500 Hz). The root mean square (RMS) values of each session was computed by averaging from each mono polar recorded across all 64 electrodes deployed. The calculated period were performed corresponding to those cropped raw EMG signals. Namely, it was conducted consecutively over each 60 sec of the entire 5 min (300 sec) (300 sec results in 5 epochs).

Simultaneously, the RMS calculation was conducted through a sub-calculation of a sequence of 200ms windows throughout the 60s interval. In the same times, each result from 200ms window calculation will be normalized by the reference value, obtained from a standard isometric test contraction, which was an outcome from the section 5.1.1). Afterward, all five RMS results obtained from each consecutive 60s epoch were then averaged into one mean at the end.

In this case, the flowchart diagrams can be described in five main consecutive steps consisting of:

a) File loading section
b) Mapping electrode grids and filtering recorded raw data
c) Calculating each epoch of normalized RMS value
d) Calculating averaged RMS across all grids and presenting out put
e) Final arrangement of RMS value and output presentation

5.1.2.1) Averaged RMS calculation

5.1.2.1 a) File loading section

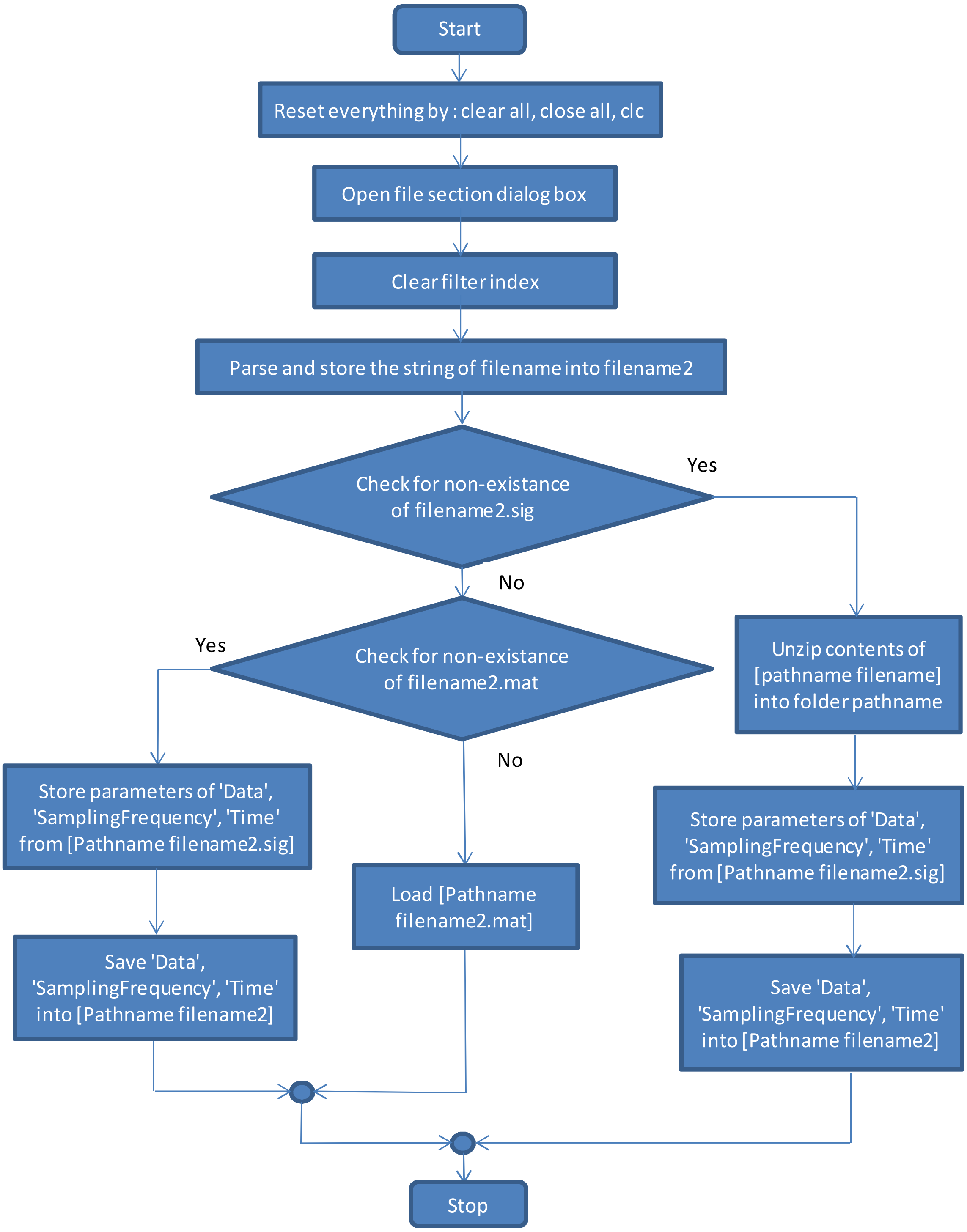

Figure 50. Flowchart diagram of averaged RMS calculation for file downloading section.

5.1.2.1 b) Mapping electrode grids and filtering recorded raw data

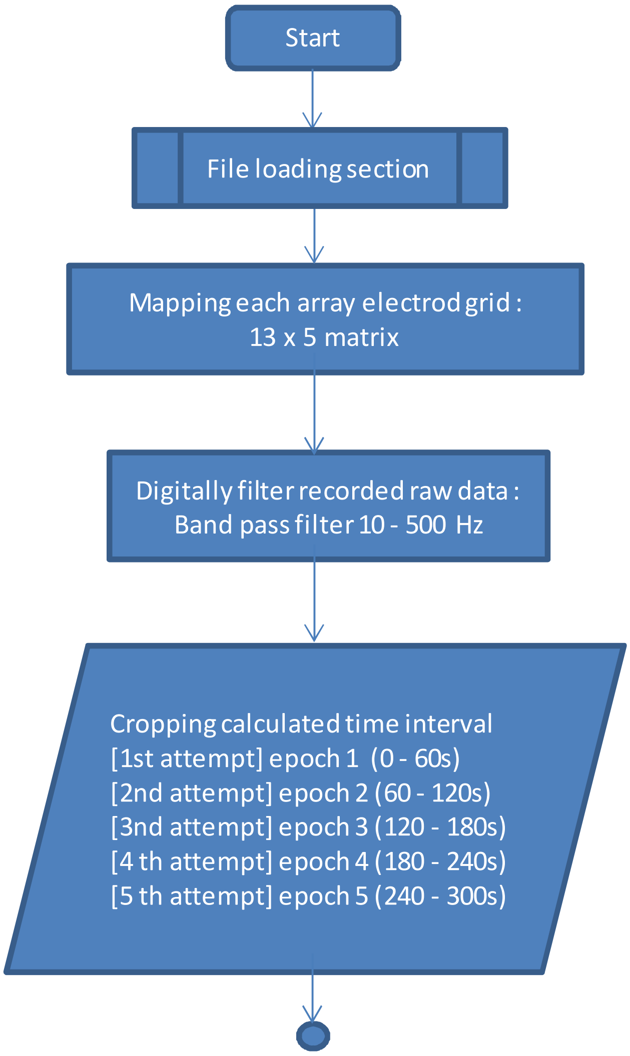

Figure 51. Flowchart diagram of averaged RMS calculation for mapping electrode grids and filtering recorded raw data.

5.1.2.1 c) Calculating each epoch of normalized RMS value

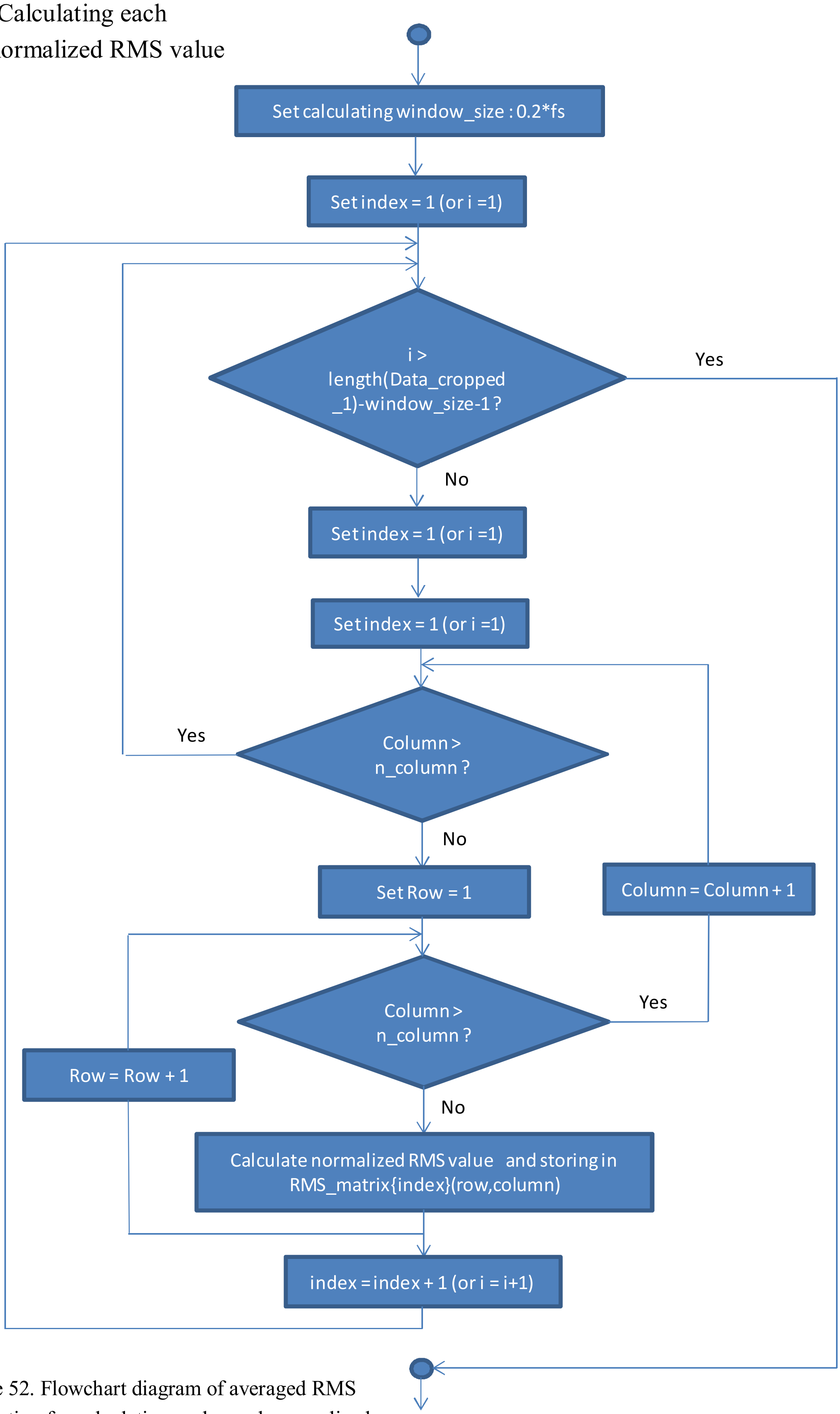

Figure 52. Flowchart diagram of averaged RMS calculation for calculating each epoch normalized RMS

5.1.2.1 d) Calculating averaged RMS across all grids and presenting output

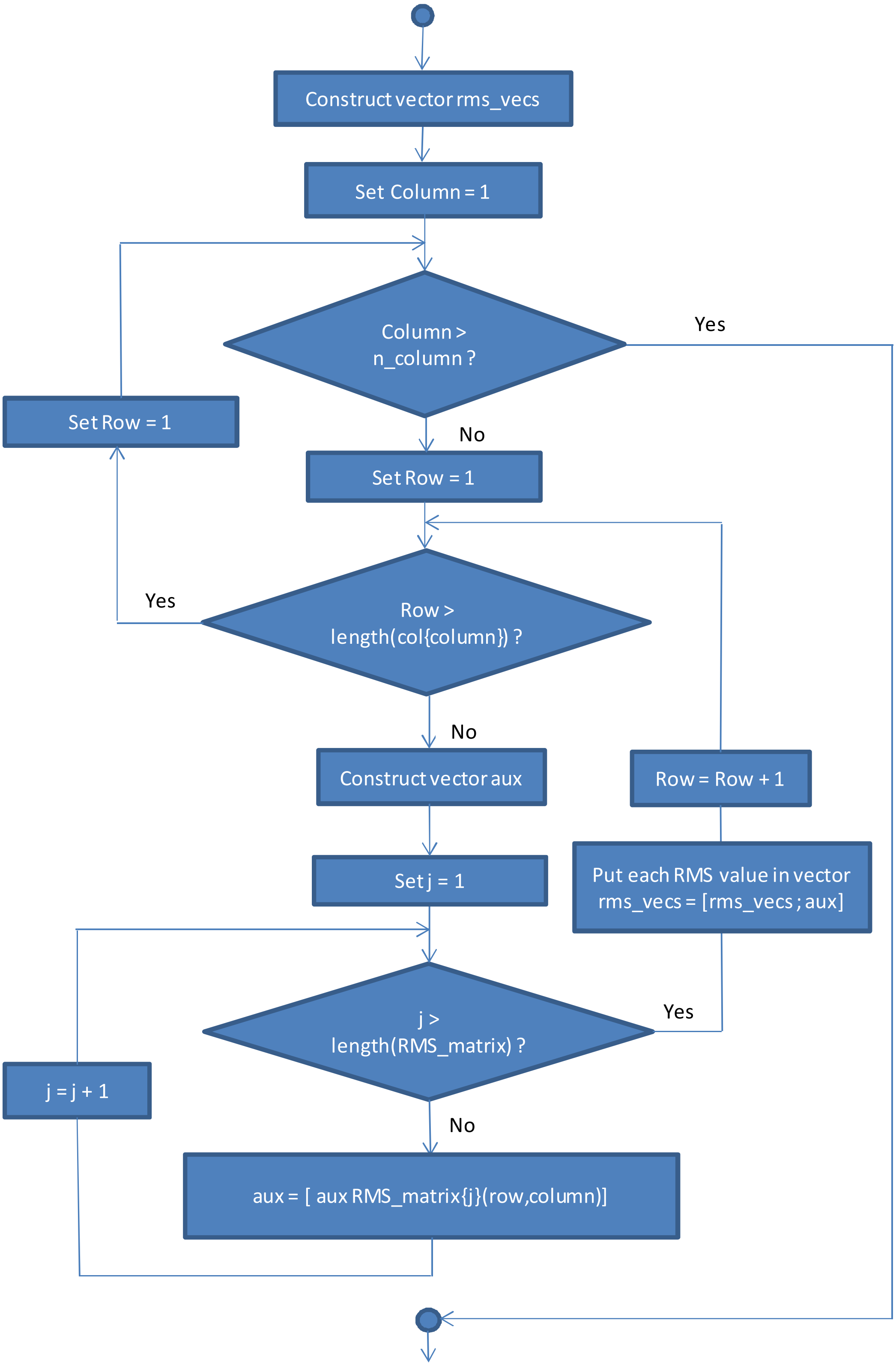

Figure 53. Flowchart diagram of averaged RMS calculation for calculating averaged RMS across all grids and presenting output.

5.1.2.1 e) Final arrangement of RMS value and output presentation

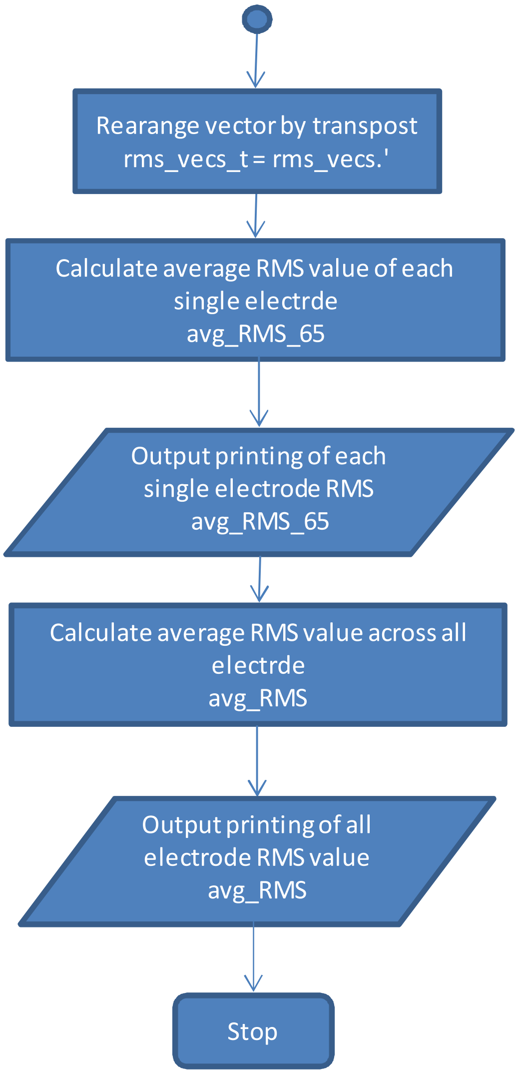

Figure 54. Flowchart diagram of averaged RMS calculation for final arrangement of RMS value and output presentation.

5.1.2.2 The averaged median frequency of power spectral (MDF) calculation

In this subsection, by corresponding with the RMS calculation, the raw surface EMG signals of every dynamic-task session was cropped consecutively over every 60 sec across the entire 300 sec of each recorded session period. Sequentially, it was off-line band-pass filtered (2nd order Butterworth filter; -3 dB bandwidth, 10 to 500 Hz). The averaged median frequency of each power spectral (MDF) values was computed by averaging all results from each monopolar recorded across all 64 electrodes. The calculated periods were performed corresponding to those cropped raw EMG signals. Namely, it was conducted consecutively over each 60 sec of the entire 5 min (300 sec = 5 calculation intervals), which is a recorded period of each session.

Simultaneously, the Hamming window of 500 samples with 50% overlapping was used in a power spectral distribution (PSD) and MDF calculation (Fs = 2000 Hz; 1 sample → 0.5ms; 500 sample = 250ms plus with 50% overlapping). The obtained MDF values were then averaged over 60s calculating period, which will be averaged once again across the 5 consecutive calculation period each 1 session. Finally, the considered result was calculated from the average of all MDF values across 64 electrodes.

In this case, the flowchart diagrams can be described in six main consecutive steps consisting of:

a) File loading section
b) Mapping electrode grids and filtering recorded raw data and determine time interval
c) Arranging data for MDF value calculation
d) Calculating averaged MDF of each electrode and their output presenting
e) Calculate averaged MDF value across all electrodes grids and its output presenting
f) Final arrangement of MDF value and output for only electrode on column 5, row 13.

5.1.2.2) Averaging MDF calculation

5.1.2.2 a) File loading section

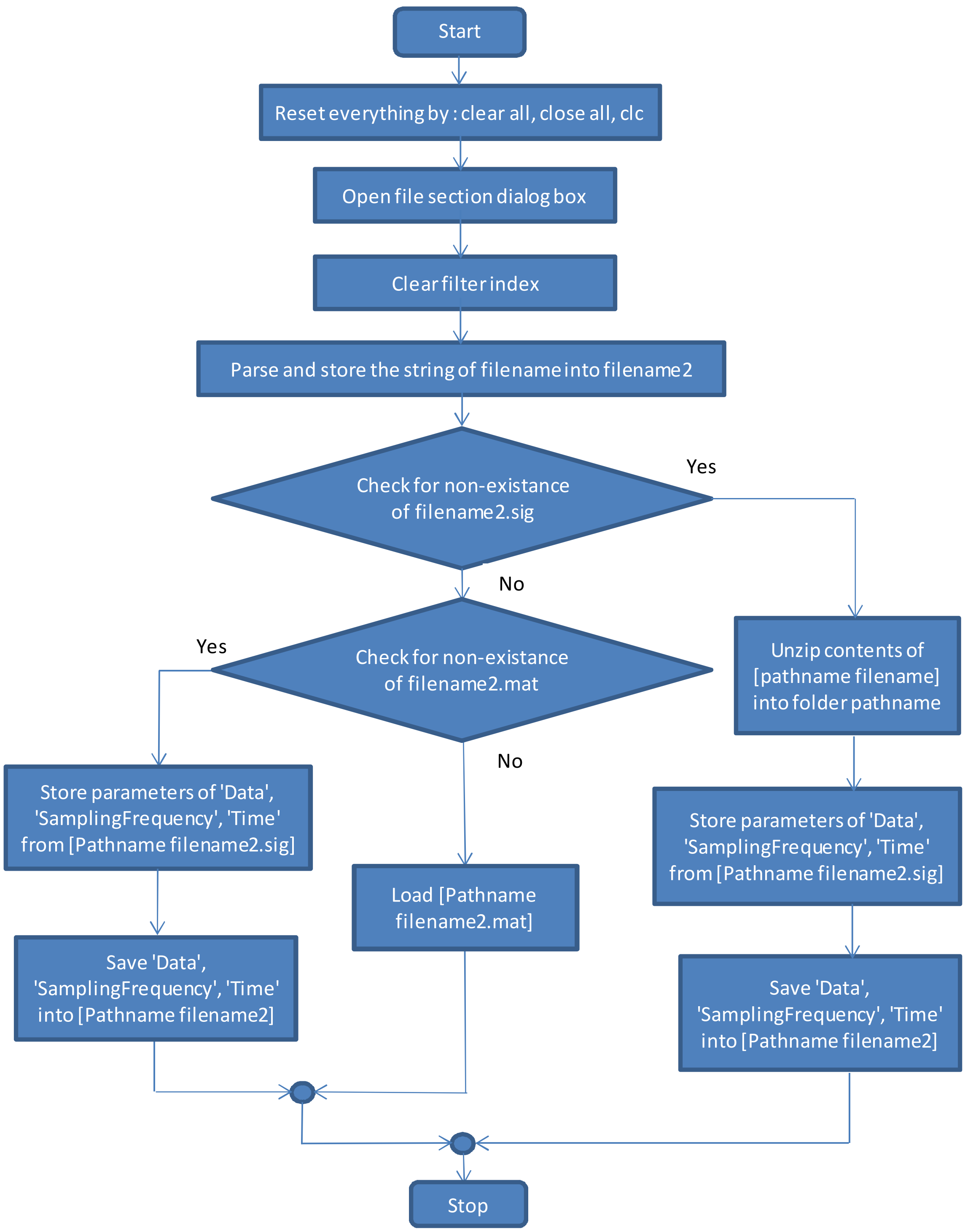

Figure 55. Flowchart diagram of average MDF calculation for file loading section

5.1.2.2 b) Mapping electrode grids and filtering recorded raw data and determine time interval

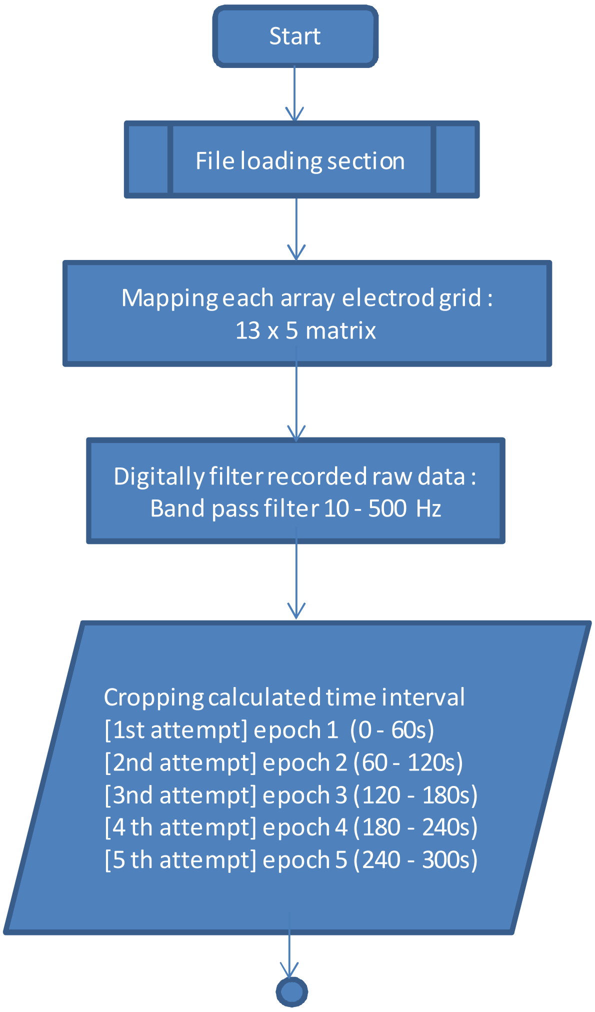

Figure 56. Flowchart diagram of average MDF calculation for mapping electrode grids and filtering recorded raw data and determine time interval.

5.1.2.2 c) Arranging data for MDF value calculation

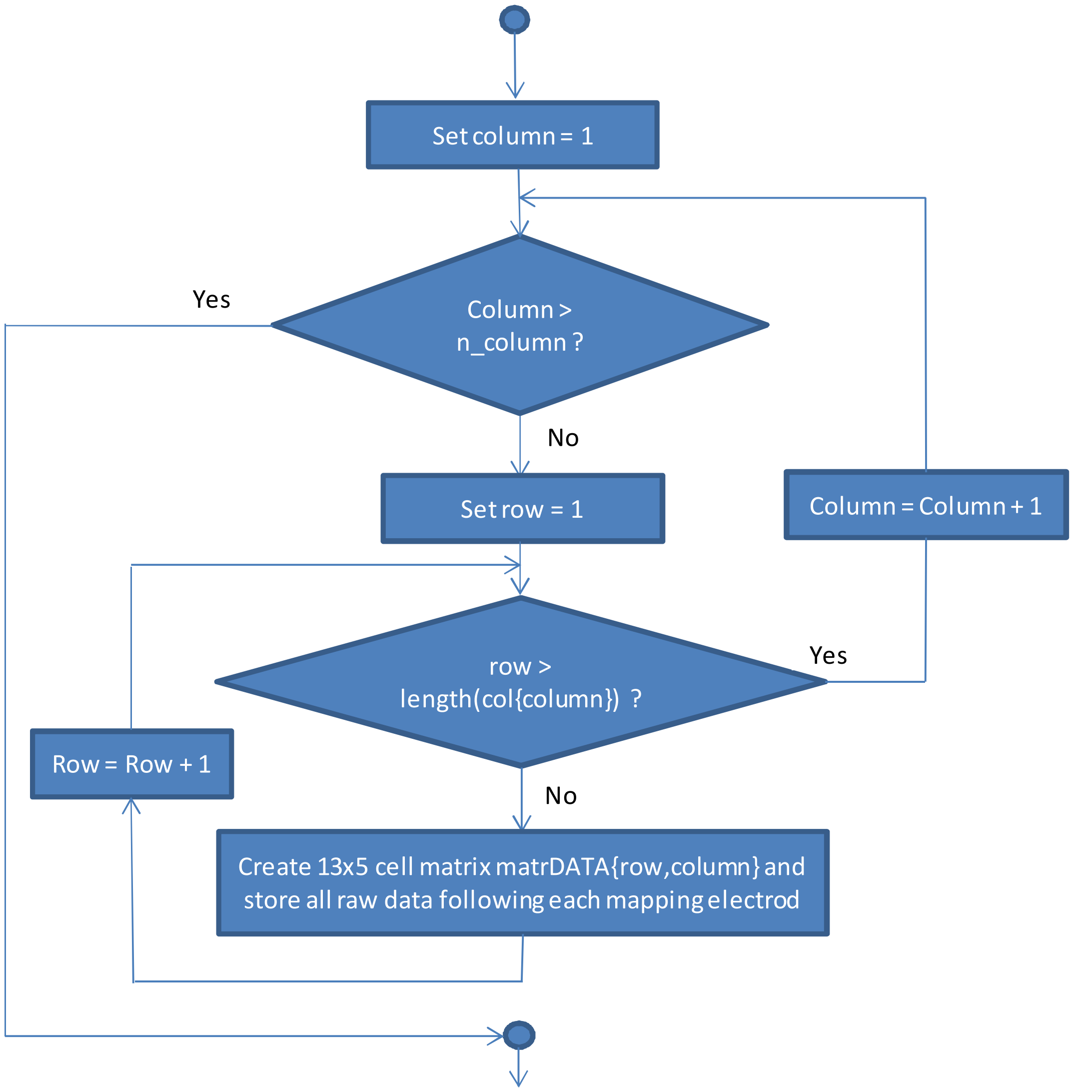

Figure 57. Flowchart diagram of average MDF calculation for arranging data for MDF value calculation.

5.1.2.2 d) Calculating averaged MDF of each electrode and their output presenting

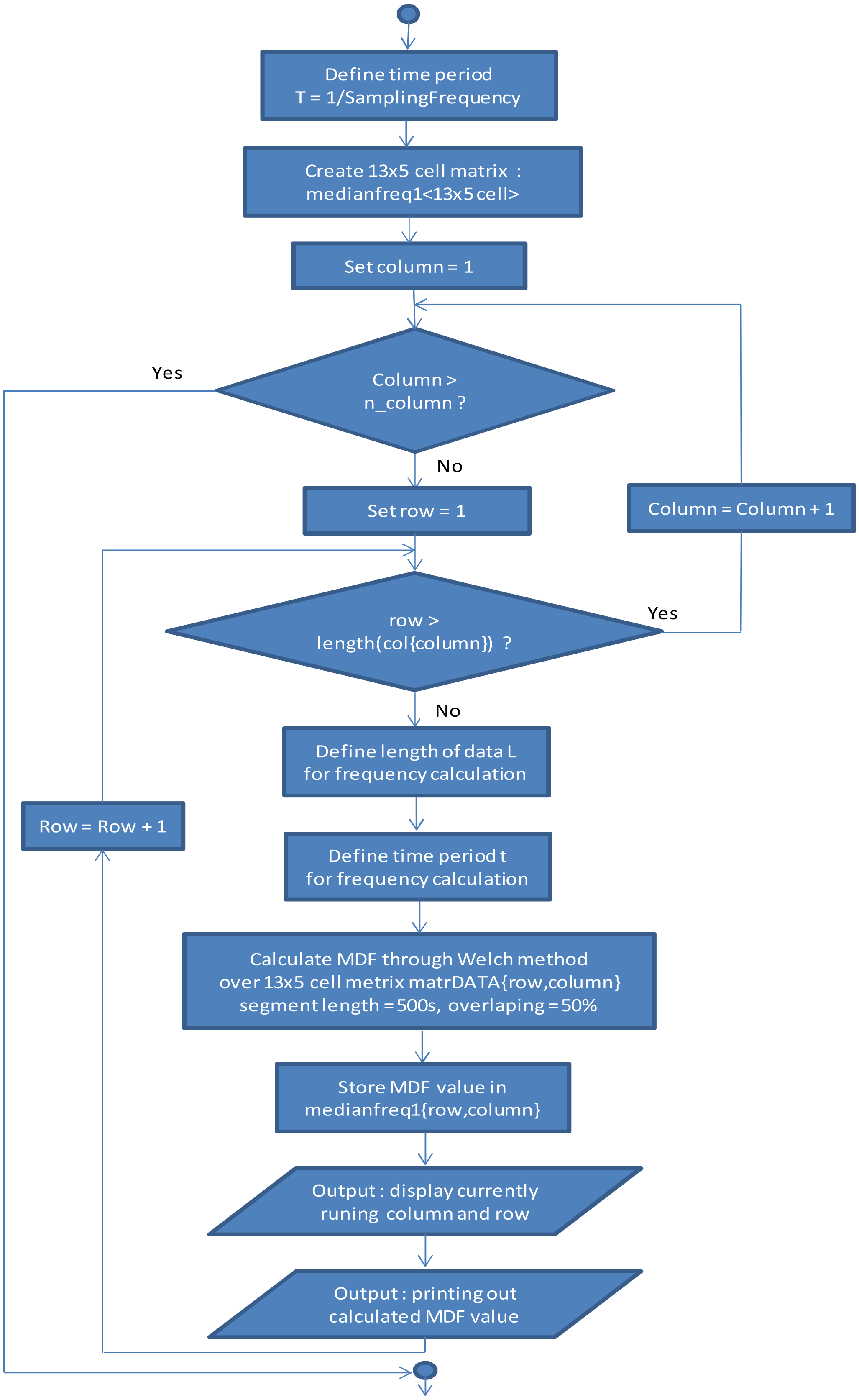

Figure 58. Flowchart diagram of average MDF calculation for calculating averaged MDF of each electrode and their output presenting

5.1.2.2 e) Calculating averaged MDF value across all electrode grids and its output presentation

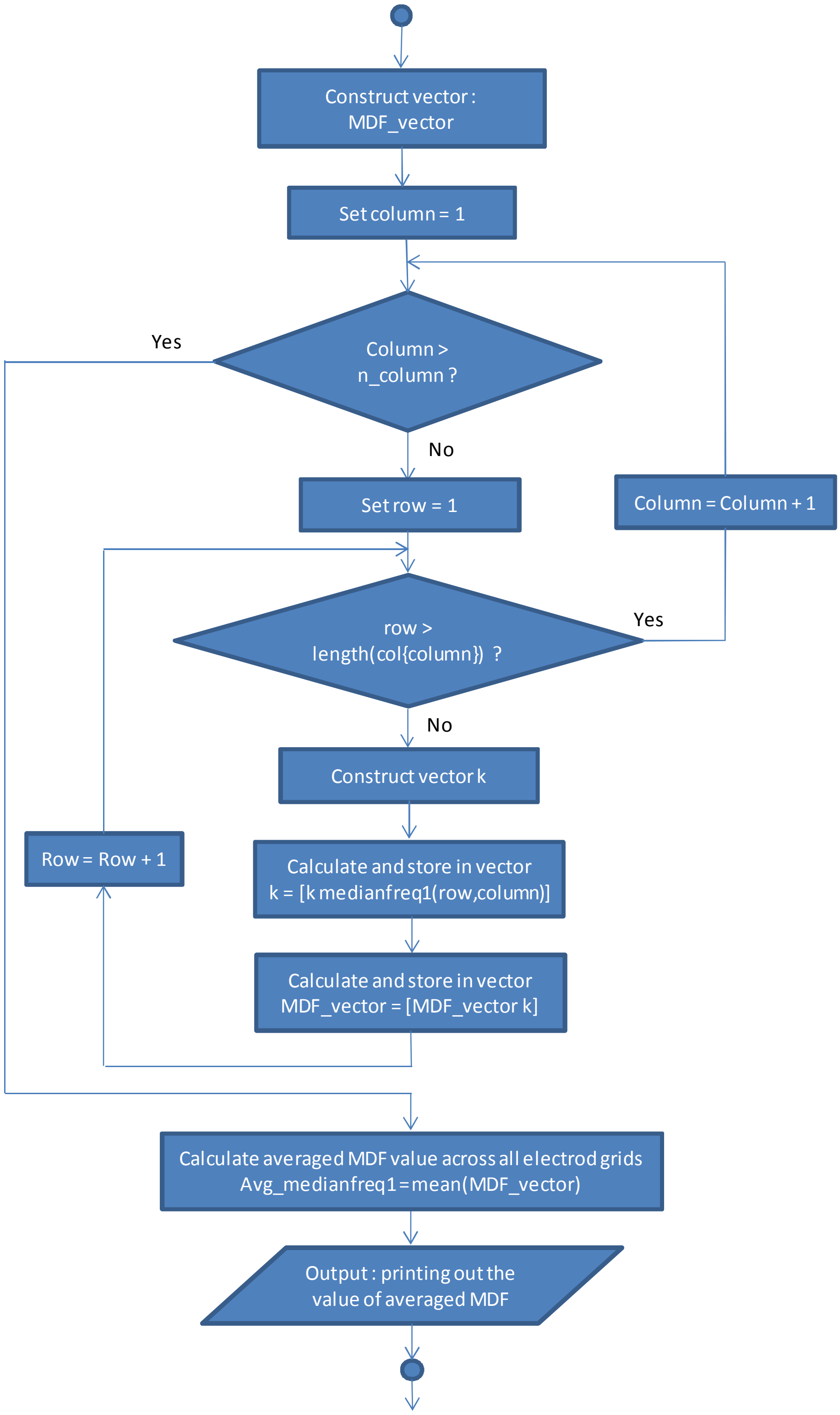

Figure 59. Flowchart diagram of average MDF calculation for calculating averaged MDF value across all electrode grids and its output presentation

5.1.2.2 f) Final arrangement of MDF value and output for only electrode on column 5, row 13

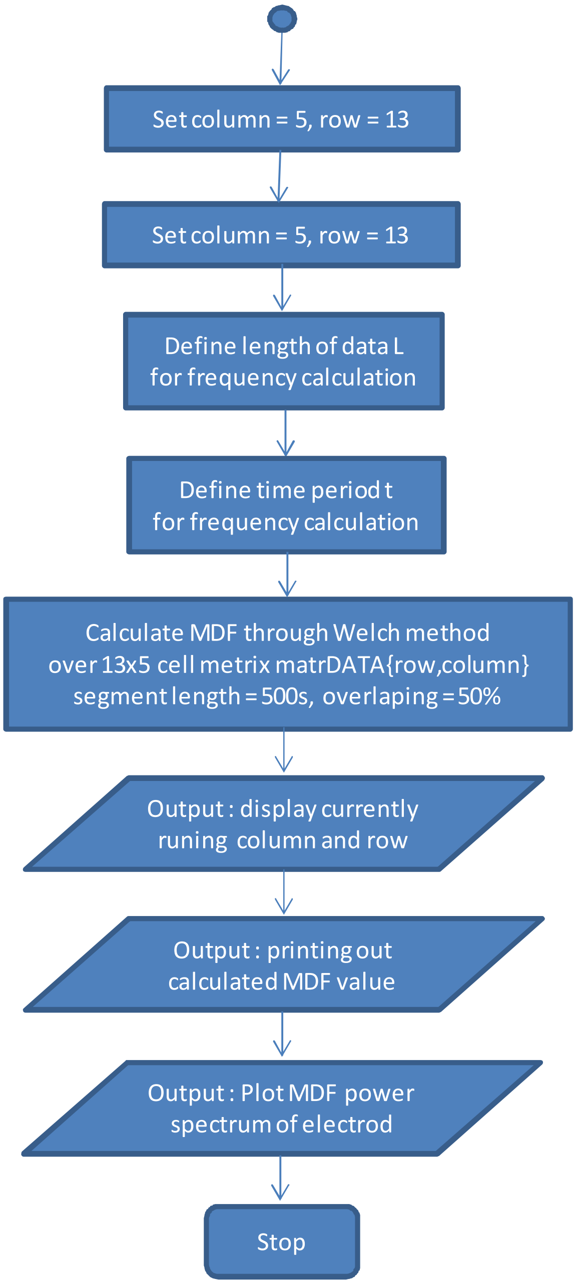

Figure 60. Flowchart diagram of average MDF calculation for final arrangement of MDF value and output for only electrode on column 5, row 1.

6 RESULTS

The results were demonstrated in averaged EMG amplitude, averaged EMG MDF and averaged local perceived fatigue. They were determined over every task session, which means 4 times a day of workday, ranging from task1 → task2 → task3 → task4. Moreover, the study was intentionally performed covering a week, in an attempt to be able to determine the impact of fatigue development throughout the workweek. Consequently, they were then divided into two consecutive periods of Week-Day, consisting of the beginning and ending period of Week-Day.

The beginning period of Week-Day was the study period performed over Monday – Wednesday, and the ending period of Week-Day was conducted over Thursday – Friday. For all detailed information, they were organized to be presented via their fatigue development parameters, whether the associated EMG parameters or local perceived discomfort as demonstrated as following.

6.1 Average EMG amplitude

The averaged EMG amplitude of classified medical diagnosis factor was statistically significant against both task and Week-Day factors (ANOVA: F = 3.286, P = 0.044; figure 61 and figure 62). For task factor, the averaged EMG amplitude of classified medical diagnosis was significantly different in statistics (ANOVA: F = 4.408, P = 0.016). A post-hoc test revealed that, the averaged RMS of healthy subjects was statistically different from shoulder MSDs subjects, across the different tasks (ANOVA: F = 4.408, P = 0.016; LSD: P = 0.045), and also statistically different from elbow & wrist MSDs subjects (ANOVA: F = 4.408, P = 0.016; LSD: P = 0.014). For the Week-Day factor, the averaged EMG amplitude of classified medical diagnosis was significantly different in statistics (ANOVA: F = 3.842, P = 0.026). A post-hoc test revealed that, the averaged RMS of healthy subjects was statistically different from shoulder MSDs subjects, compared between the beginning period of Week-Day (Mon - Wed) and the ending period of Week-Day (Thu - Fri) (ANOVA: F = 3.842, P = 0.026; LSD: P = 0.039), and also statistically different from elbow & wrist MSDs subjects (ANOVA: F = 3.842, P = 0.026; LSD: P = 0.011), For the missing of elbow & wrist in the ending period of Week-Day, this may have contributed to the non-statistic difference between shoulder MSDs and elbow & wrist MSDs over this case. For all details, it could be explained case by case as following:

6.1.1 The beginning period of Week-Day (Mon – Wed) of averaged EMG amplitude

For the beginning period of Week-Day (Mon – Wed), its results can be illustrated graphically in figure 61. For the healthy subjects, their averaged RMS of upper trapezius started increasing pretty sharply from 103.7% - 122.7% during the first phase (task1 – task2), and still kept going up during the second phase (task2 – task3) but with a less increasing slope than in the first phase, namely from 122.7% - 123.7%, and then remaining rising with relatively more increasing slope again during the last phase of the day (task3 – task4) from 123.7% - 129.7%. For Shoulder MSDs subjects, their averaged RMS of upper trapezius started decreasing at the first phase (task1 –

task2) from 135.1% – 128.8%, and then still continued decreasing during the second phase (task2 – task3) from 129.7% - 121.3%, before turning into an increase with relatively sharp, during the last phase of the day (task3 – task4) from 121.3% - 150.9%. For elbow & wrist MSDs subjects, their averaged RMS of upper trapezius started increasing relatively sharp from 128.4% - 168.5% during the first phase (task1 – task2), and then it inversely started decreasing during the second phase (task2 – task3) from 168.5% - 162.5%, before remaining decreasing from 162% - 157.7% during the last phase of the day.

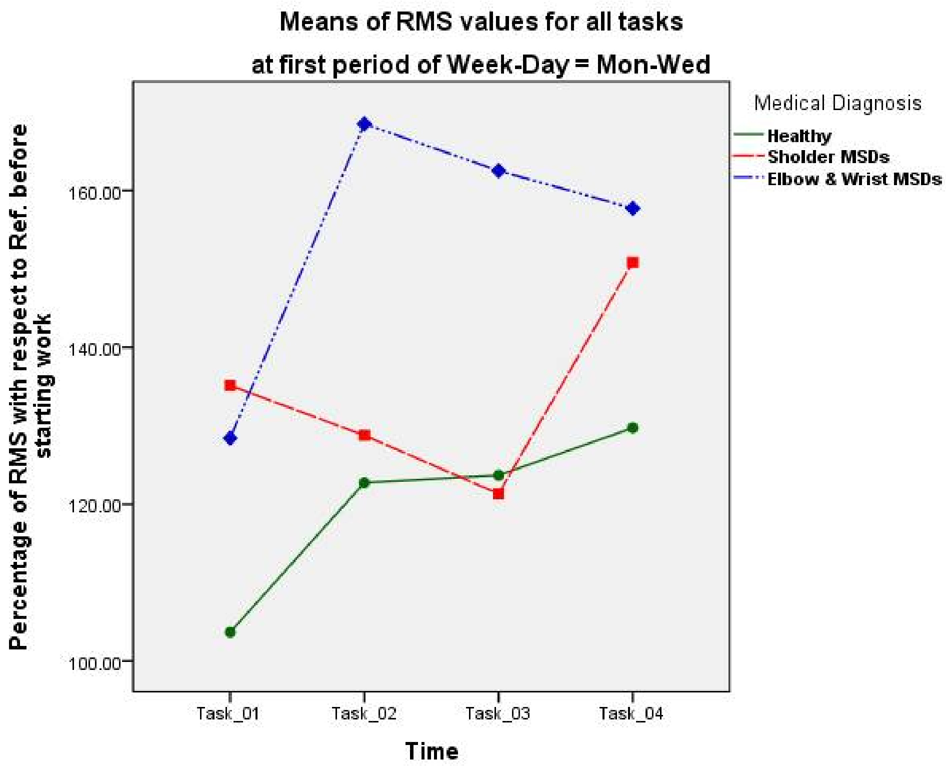

Figure 61. Mean of RMS values of all tasks at the beginning period of Week-Day (Mon – Wed).

6.1.2 The ending period of Week-Day (Thu – Fri) of averaged EMG amplitude

For the ending period of Week-Day (Thu – Fri), it results can be graphically shown all in figure 62. It appears that, the healthy subjects averaged RMS of upper trapezius started increasing from 108.8% - 113% during the first phase of the day (task1 – task2), before decreasing from 113% - 108.8% during the second phase (task2 – task3), and then still remaining decreasing, but with very slightly in slope during the last phase of the day (task3 – task4) from 108.8% - 108.7%. For the shoulder MSDs subjects, the average RMS of upper trapezius started decreasing relatively sharp from 171.7% - 133.5% during the first phase of the day (task1 – task2), and then still remained decreasing during the second phase (task2 – task3), with lower decreasing slope from

133.5% - 122.5%, for the last phase of the day (task3 – task4), the RMS value turned to an increase inversely with relatively high increasing slope from 122.5% - 165.7%.

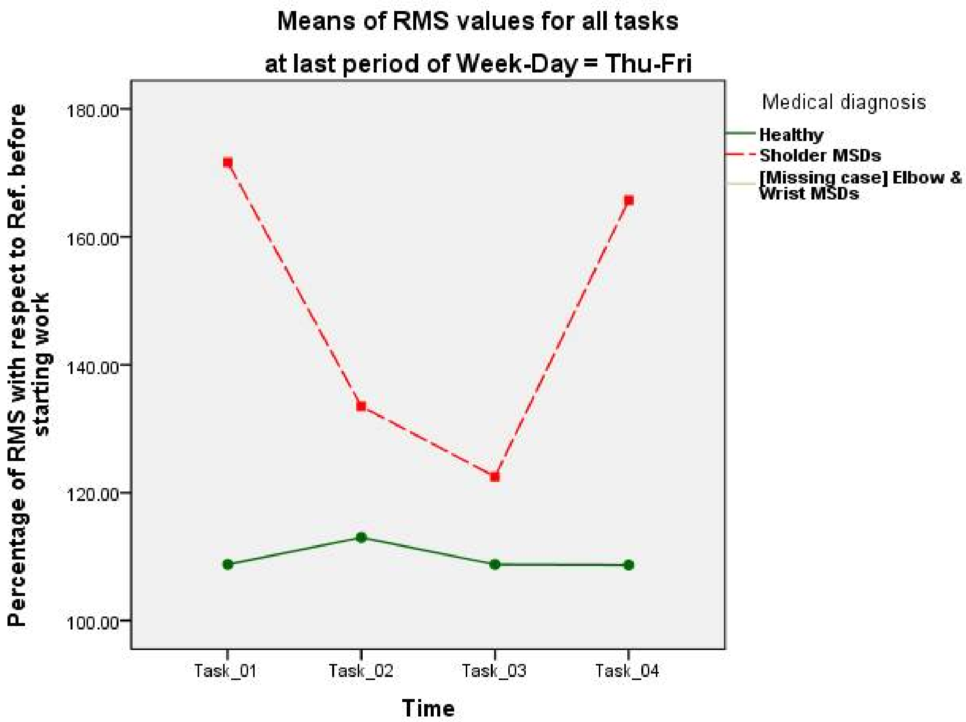

Figure 62. Mean of RMS values of all tasks at the ending period of Week-Day (Thu – Fri).

6.2 Averaged EMG MDF

The average EMG MDF values were not statistically significant at 0.05 in all kind of relations of this study. However there were some interesting statistical information including, each of its main factors as following: task (ANOVA: F = 1.409, P = 0.249), classified medical diagnosis (ANOVA: F = 0.169, P = 0.845) and Week-Day (ANOVA: F = 1.018, P = 0.317). Anyway these may have told use for some significant trend of fatigue development signs, particularly through each independent parameter, which will be described in details below, although they are not significant at 0.05 in statistics.

6.2.1 The beginning period of Week-Day (Mon – Wed) of averaged EMG MDF

For the beginning period of Week-Day (Mon – Wed) as illustrated graphically in figure 63. It appears that, the healthy subjects averaged MDF of upper trapezius started decreasing rapidly from 39.7 Hz – 34.4 Hz during the first phase (task1 – task2), and still continuing going down during the second phase (task2 – task3) from 34.4 Hz – 30.34 Hz, and then still remaining decreasing, but with smaller decreasing slope during the last phrase of the day from 30.34 Hz –

29.9 Hz. For the shoulder MSDs case, the average MDF of upper trapezius started decreasing from 34.5 Hz – 33.3 Hz during the first phase (task1 – task2), and then still kept decreasing during the second phase (task2 – task3) from 33.3 Hz – 27.3 Hz, then still remaining decreasing during the last phrase of the day (task3 – task4) from 27.3 Hz – 25.7 Hz. For elbow and wrist subjects, the averaged MDF of upper trapezius started decreasing from 38.6 Hz, noticeably pretty close to the healthy subjects, before decreasing down sharply to 28.6 Hz at the second task. This averaged MDF of upper trapezius of elbow & wrist case still remained decreasing during the second phrase (task2 – task3), but with smaller decreasing slope from 28.6 Hz – 26 Hz, before remarkably turning to an increase very sharply from 26 Hz – 35.8 Hz during the last phrase of the day (task3 – task4).

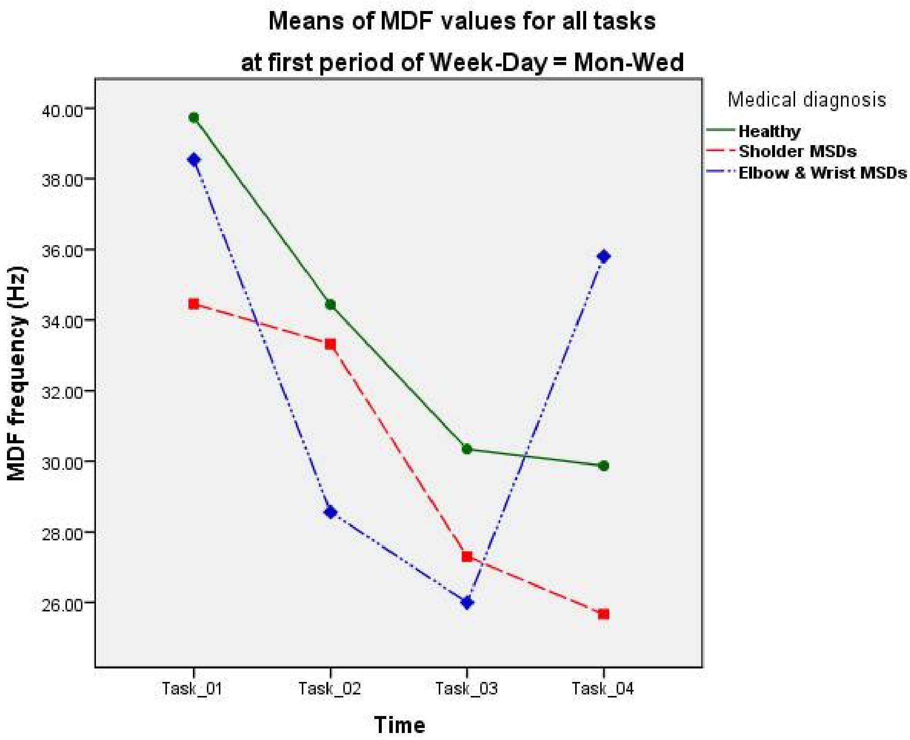

Figure 63. Mean of MDF values of all tasks at the beginning period of Week-Day (Mon – Wed).

6.2.2 The ending period of Week-Day (Thu – Fri) of averaged EMG MDF

For the ending period of Week-Day (Thu – Fri) as presented in figure 64, the healthy subjects averaged MDF of upper trapezius decreased slightly from 29.4 Hz – 29.2 Hz during the first phrase (task1 – task2) of the day, and then still continuing decreasing during the second phrase (task2 – task3) from 29.2 Hz – 27.8 Hz, before turning to an increase during the last phrase (task3 – task4) from 27.8 Hz - 29 Hz. For the shoulder MSDs case, the average MDF of upper trapezius started a rapidly extreme decrease from 38 Hz – 25.5 Hz during the first phase (task1 – task2), and then likely to stay constant over the rest of the tasks, namely remaining unchanged during the second phrase (task2 – task3), and then very slightly increasing from 25.5 Hz - 25.7 Hz during the last phrase of the day (task3 – task4).

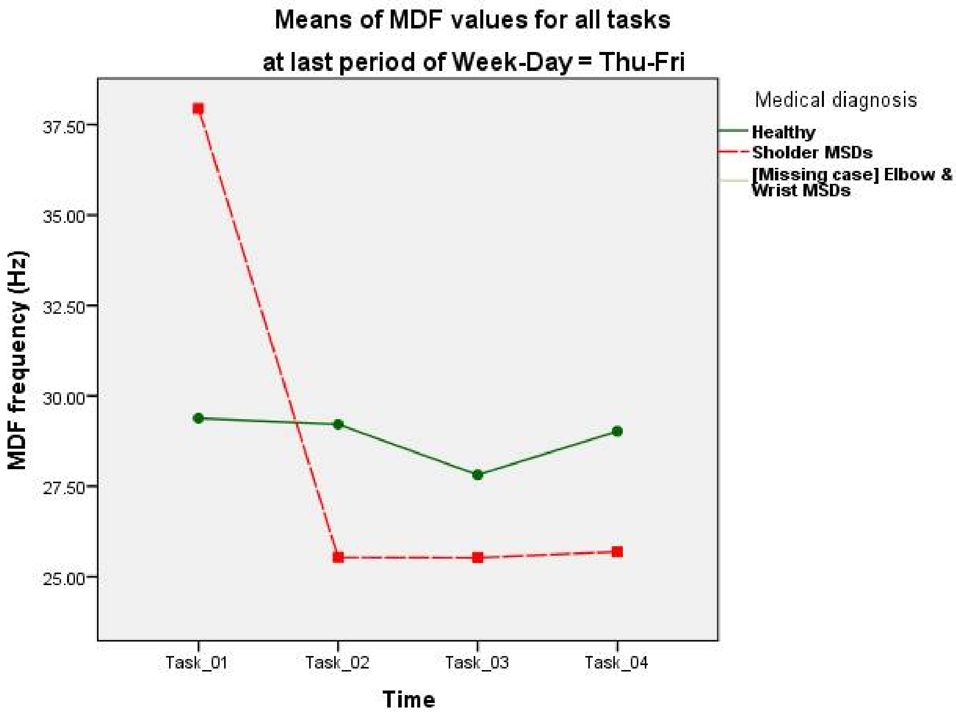

Figure 64. Mean of MDF values of all tasks at the ending period of Week-Day (Thu – Fri)

6.3 Averaged local perceived discomfort

The averaged local perceived discomfort over shoulder and neck of medical diagnosis factor was statistically significant against both task and Week-Day factors (ANOVA: F = 5.366, P = 0.007; figure 65 and 66). For the time factor, the averaged local perceived discomfort of classified medical diagnosis was significantly different in statistics (ANOVA: F = 5.056, P = 0.009). A post-hoc test revealed that, the averaged perceived fatigue of shoulder MSDs subjects was statistically different from the healthy ones, affecting across all different tasks (ANOVA: F = 5.056, P = 0.009; LSD: P = 0.005), and moreover, it was also statistically different from the elbow & wrist MSDs subjects (ANOVA: F = 5.056, P = 0.009; LSD: P = 0.017). However, there was no statistically significant difference among the healthy subjects and the elbow & wrist ones (ANOVA: F = 5.056, P = 0.009; LSD: P = 0.497). For the Week-Day factor, the average local perceived discomfort of classified medical diagnosis was significantly different in statistics (ANOVA: F = 5.832, P = 0.04). A post-hoc test revealed that, the average local perceived discomfort of shoulder MSDs subjects was statistically different from the healthy ones between the beginning period of Week-Day (Mon - Fri) and the ending period of Week-Day (Thu - Fri) (ANOVA: F = 5.832, P = 0.04; LSD: P = 0.04), and also statistically different from the elbow &

wrist MSDs ones (ANOVA: F = 5.832, P = 0.04; LSD: P = 0.014). However, there was no statistically significant difference among the healthy subjects and the elbow & wrist ones (ANOVA: F = 5.832, P = 0.004; LSD: P = 0.489), which may have been due to the missing of elbow & wrist in the ending period of Week-Day. For all deeper details, it could be explained case by case as following:

6.3.1 The beginning period of Week-Day (Mon – Wed) of averaged local perceived discomfort

For the beginning period of Week-Day (Mon – Wed) as illustrated graphically in figure 65, the healthy subjects averaged local perceived discomfort of shoulder and neck started increasing from 1.33 – 1.67 during the first phase (task1 – task2), and remained constant on the second phase (task2 – task3) at 1.67, before starting rising again with relatively high increasing slope, during the last phase of the day (task3 – task4) from 1.67 – 2.17. For the shoulder MSDs subjects, the averaged local perceived discomfort of shoulder and neck started increasing at the first phase (task1 – task2) from 1.25 – 1.5, and still continuing an increase, but with very sharply during the second phase (task2 – task3) from 1.5 – 3.25, and still remaining increasing during the last phase of the day (task3 – task4) from 3.25 – 3.75. For the elbow & wrist MSDs subjects, the averaged local perceived discomfort of shoulder and neck started rising from 0.5 – 1.0 during the first phase (task1 – task2), and remained steadily over the second phase (task2 – task3) at 1.0, before starting increasing again during the last phase of the day (task3 – task4) from 1.0 – 1.5

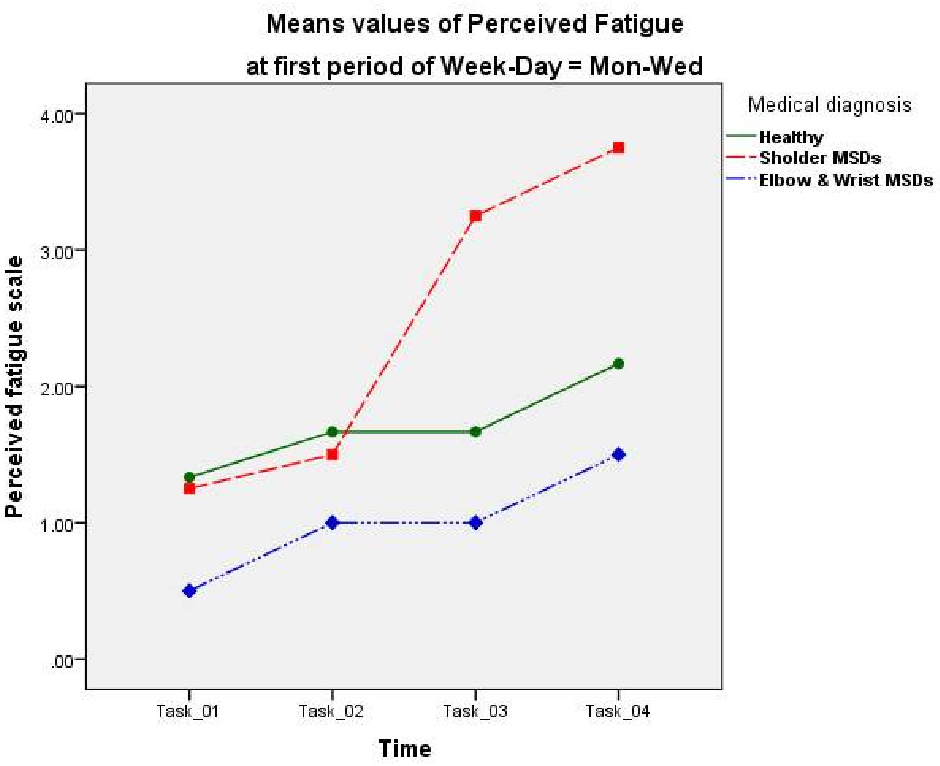

Figure 65. Mean of local perceived fatigue of all tasks at the first period of Week-Day (Mon–Wed).

6.3.2 The ending period of Week-Day (Thu – Fri) of averaged local perceived discomfort

For the ending period of Week-Day (Thu – Fri) as illustrated graphically in figure 66, the healthy subjects averaged local perceived discomfort of shoulder and neck started increasing from 1 – 1.14 during the first phase (task1 – task2), and remaining steadily on the second phase (task2 – task3) at 1.14, before starting rising again with a slightly change in slope during the last phase of the day (task3 – task4) from 1.14 – 1.29. For the shoulder MSDs subjects averaged local perceived discomfort of shoulder and neck started decreasing at the first phase (task1 – task2) from 4.0 – 3.0, and then remaining constant over the rest of the remaining tasks of the day (task2 – task3 – task4) at 3.0.

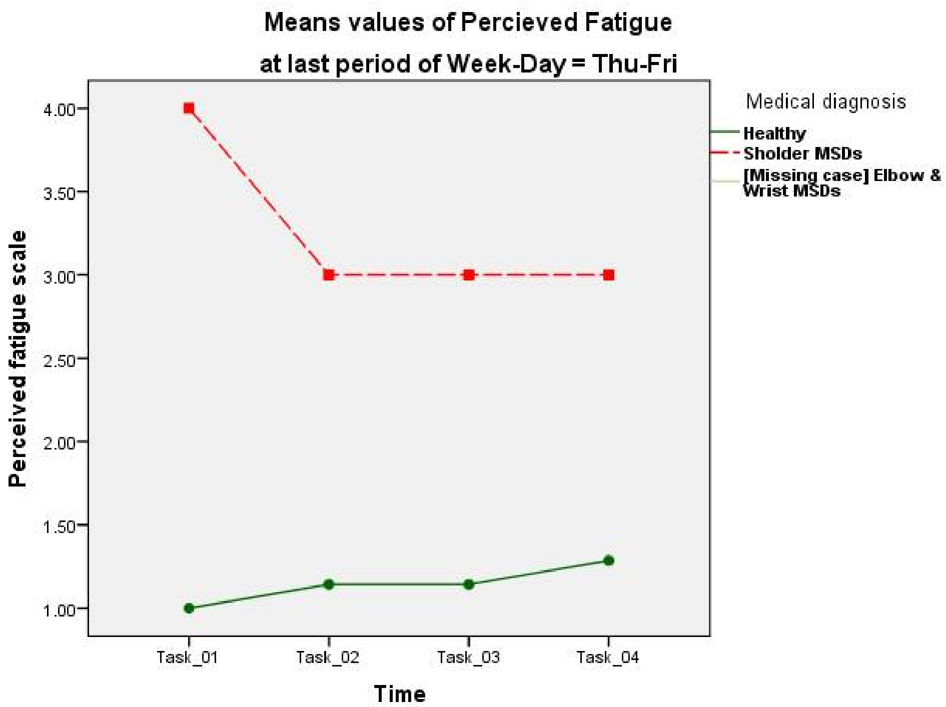

Figure 66. Mean of local perceived discomfort of all tasks at the ending period of Week-Day (Thu–Fri).

7 DISCUSSION

In this section, all related information and possible theories will be gathered and integrated in the discussion, in an attempt to explain all phenomenal occurring during the fatigue studying period. The dependent parameters, including averaged RMS, averaged MDF and averaged local perceived discomfort will be organized to be described via each consecutive work phase (first phase, second phase and the third phase of the day), throughout the workday and all over Week-Day.

Accordingly, with the different cases of muscle health condition participating in the research, it is highly expected to enhance an understanding and knowledge of the fatigue development found in this study, particularly occurring in the real-world working condition. In order that, this study would help develop some possibly alternative ways to control and prevent those workers from any MSDs work-related treat in the future.

7.1 The beginning period of week-day (Mon – Wed)

7.1.1 First phase of the day (task1 – task2)

a) Averaged RMS value

For the averaged RMS parameter, it was obviously observed that, the averaged RMS values obtained from the healthy subjects started increasing in relatively pretty high slope from 103.7% - 122.7% (slope +19), with respect to the reference value, measured at the beginning of the workday. This represented the development of higher activation over the muscle being investigated. This phenomenal could be explained as the increasing sign of fatigue, indicated by an increase of RMS value (Kallenberg et al., 2007, Madeleine et al., 2002, Merletti et al., 2002, Merletti et al., 1990). This is a result of the requirement of workload over time across the first phase. Therefore, the active muscles had to employ additional MUs recruitment, in an effort to cope with this, and remarkably those additional recruited ones were generally coming with the bigger size and higher-threshold MUs, according to the size principle (Andreassen and Arendt-Nielsen, 1987, Henneman E et al., 1965, Kallenberg et al., 2007). Subsequently, this eventually led to the higher value of averaged RMS of EMG signals being detected (Roeleveld et al., 1997).

For the elbow & wrist MSDs subjects (with healthy shoulder condition), the averaged RMS value also increased with relatively higher increasing slope, with respect to the healthy one, ranging from 128.4% - 168.5% (slope +40.1), and remarkably its starting point (128.4%) was relatively high, and considerably much higher than in the healthy one (103.7%). This phenomenal could have been described as the effect from their abnormality over the histological and morphological changes, occurring over elbow & wrist portions. Although, it (abnormality portions: elbow & wrist) wasn't right at the shoulder, being measured by the surface EMG arrays electrode, but since these affected workers had to deal with the relatively same workload as performed by the healthy ones, as well as the fatigue and pain that may be developed very quickly or even already existing and having badly gone further worse across the task. This pain may have led to the alteration of muscle control strategy over elbow & wrist, reorganized by the workers suffering with this problem, in order to maintain the task performance, with respect to the healthy ones.

This muscle control strategy alteration could have been due to the nociceptive afferent activity, leading to the reduction of the muscle activation over the affected portions, including elbow and wrist (no EMG measurements on both elbow and wrist in this study), then consequently contributing to the distribution of load among synergistic muscles (Falla and Farina, 2005a, Kallenberg et al., 2007, Szeto GPN et al., 2003). In this case, it may have resulted in the limitation of movements from both elbow and wrist portions, leaving the shoulder seemingly had to play a critical role of carrying out the loads excessively and desperately. Hence, it likely resulted in the relatively high increasing slope, and much higher starting value of the observed averaged RMS, compared with the healthy ones case, which had all portions smoothly working with all together in excellent cooperation.

For the shoulder MSDs subjects, the average RMS value appeared to inversely decrease from 135.1% - 128.8% (slope -6.3), and noticeably, its starting value was very relatively high, and becoming the highest one of all cases. This could remarkably have been described as the effect from their abnormality over the histological and morphological changes, occurring over shoulder, where EMG signals were exactly being detected. Instead of increasing over time as same as the others, but it was being in the opposite way, this would have been due to the alternation of muscle strategy over shoulder, which is the result of the histological and morphological changes.

By this, in order to cope with the same workload, with respect to the healthy ones, the affected shoulders apparently had to participate in this effort anyways, despite the appearance of muscle abnormality and probably existing pain, as demonstrated in the starting value of the averaged RMS, that was very high and becoming the highest one, compared with either healthy or elbow & wrist case. This had indicated the relative extreme muscle activities, which on one hand, it might have demonstrated the extreme fatigue occurring since the very early task, in fact at the first task of the workday, since the increase of RMS value (in this rear specific case demonstrated by the highest value followed by the decreasing one) is associated to myoelectric signs of fatigue (Kallenberg et al., 2007), in general the higher value implies the greater fatigue that it could be. But in this specific case, the tendency of RMS was decreasing over time through the first phase, this could have been explained as just a result from the fatigue, having developed very quickly since the first phase, and finally quickly contributing into pain over the suffering muscle.

By this, the workers with shoulder MSDs may have adopted the alteration of muscle control strategy over the shoulder, driven by nociceptive input to spinal and supraspinal circuitries, which resulted in reducing the descending drive to the muscle, contributing to the reduction of activation of such painful muscle (Falla et al., 2010, Farina et al., 2004a, Graven-Nielsen et al., 1997, Sohn et al., 2000), namely, in order to mitigate the pain, existing over the affected muscle. This adoption of the alteration of muscle control strategy over the shoulder could result in the restricted movement over the painful muscle, which in line with previous studies, investigating individuals with chronic LBP. Those results demonstrated a variety of biomechanical disturbances in various ways, including reduced acceleration of movement, decreased velocity and restricted range of motion (Magnusson et al., 1998, Shum et al., 2007, Silfies et al., 2009), With these, they had concluded that, individuals with LBP adopted the alternative movement strategy, in order to avoid the motion of painful muscle (Falla et al., 2014b).

In this case, the first phase (task1 - task2), for the second task, in order to maintain the same motor output as taking place during the first task (seemingly already fatigued, and maybe having already been transformed into pain since the first task), workers with shoulder MSDs may have adopted alteration of muscle control strategy by distribution of load through synergistic muscles, which in line with the previous studies (Falla and Farina, 2005a, Kallenberg et al., 2007, Szeto GPN et al., 2003). Remarkably, it was the same as what occurred in the elbow & wrist case, but with the different synergistic muscles distribution. In this case, it (the synergistic muscles distribution) could possibly have mainly been transferred toward hand-arm-related muscles or trunk instead.

b) Average MDF value

For all cases, the values of averaged MDF were observed decreasing, but with different conditions. In general, this phenomenal could be explained as: once muscle contraction has occurred, namely fatigue has developed, this will induce an increase of concentration of lactic acid, which is a consequence of metabolic product, due to the insufficient oxygen and nutritive substances, supplied through blood circulation, as well as a result of changes in an efficiency of the nervous system (Cifrek et al., 2009). This phenomenal contributes to a decrease in muscle fibre conduction velocity (CV) (Madeleine et al., 2002, Merletti et al., 2002, Merletti et al., 1990), indicating a larger MUAP duration (Lindstrom LH and Magnusson RI, 1977). This larger MUAP duration contributes to a lower amount of MUAP traveling over time domain, widely known as frequency in the unit of Hertz (Hz) representing the amount of travelling MUAP/sec.

For the healthy subjects, the value of MDF decreased from 39.7 Hz – 34.4 Hz (slope -5.3), while MDF value of elbow & wrist MSDs subjects decreased from 38.6 Hz – 28.6 Hz (slope -10). Both cases obviously indicated the development of fatigue over time. Noticeably, the starting value of the healthy (39.7 Hz), and the elbow & wrist (38.6 Hz) were pretty close to each other, this may have been due to the medical diagnosis results, determining no shoulder muscle fibres abnormalities existing among the elbow & wrist subjects, as same as in the healthy ones. While noticeably, there was EMG electrode array measuring only on the healthy shoulder portion of both cases (No measurement of affected elbow & wrist portions).

However, subjects with elbow & wrist demonstrated more fatigue sign (lower MDF value), and the more considerably was that, the decreasing MDF value of the elbow & wrist subjects had greater inclination slope than in the healthy ones, which this had represented a more fatigue development rate on the shoulder, with respect to the healthy ones. This may have been caused by the muscle fibre abnormalities, existing over elbow & wrist on this case. Therefore in order to cope with the task, the workers in this case may have adopted alteration of muscle control and alternative movement strategy, as described previously on 7.1.1-a) the average RMS value section (please review for more comprehensive details). In an effort to maintain the same motor output, shoulder may have had to carry out this task desperately much more than in the healthy ones, eventually leading to a greater sign of fatigue. On one hand, Subjects with shoulder MSDs were also observed a decrease of MDF value, ranging from 34.5 Hz – 33.3 Hz (slope -1.2) during this phase. Remarkably the starting value was quite low with respect to either the healthy or the elbow & wrist ones, this could represent the very relatively huge amount of fatigue occurring, compared with the others. This phenomenal could have been explained as parts of the MUs would have already been chronically fatigued, even before starting of the workday, in correspondence with the relative highest value of the average RMS, observed in the previous section.

Apparently, for its relatively less declination slope, compared with the others, this may have demonstrated the supporting hypothesis, obtained from the RMS manifestation, previously explained on the section 7.1.1-a), saying that, workers in this case may have adopted alteration of muscle control and alternative movement strategy, to mitigate the fatigue and chronically existing pain over shoulder, by reducing muscle activation through the distribution most of the mechanical load toward the synergistic muscles instead. Seemingly this manoeuvre was acting as a strategy to endure working ability till the end of the working day as well as throughout the week. Therefore, the MDF over the problematic shoulder muscle had not been observed in extreme steep declination during this phase.

c) Averaged local perceived discomfort

All cases in this phase were observed averaged local perceived discomfort increasing over time. For the healthy subjects, it was rising from 1.33 – 1.67 (slope +0.34), along with the subjects with shoulder MSDs, which rising from 1.25 – 1.5 (slope +0.25). Noticeably, it was not obviously observed much different trend among this two during this period. This therefore could be explained as the complexity of the definition of discomfort level, made by each individual, as well as the other effects that may have influence to the results, especially in the occupation setting, for instant the subjective interpretation of an intervention (e.g. longer working hours), the combination of sensations of pain, pressure, discomfort in tissues (Bosch et al., 2007). On the other hand, this may have been connected to the workers adoption of alteration of muscle control and alternative movement strategy.

For its not obviously observed much different trend among the this two cases in this phase, it may be likely that, subject with shoulder MSDs had mostly transferred muscle load toward some synergistic muscles. By this, it would enhance the muscle endurancelonger, as well as the combination between the familiarity of the pain (most of affected subjects had been working for several years), and the freshness, since it was still being in the beginning of the day.

Interestingly the significant difference was observed among subjects with elbow & wrist MSDs, with respect to the healthy and subjects with shoulder MSDs. Namely, although the local perceived discomfort of elbow & wrist was also increasing from 0.5 – 1.0 (slope +0.5), but it was obviously lower than the other two. This may have been explained through the influence from severe pains, occurring on elbow and wrist portions, which may likely have overwhelmed all feeling of discomfort away from their shoulder, with respect to the healthy ones.

7.1.2 Second phase of the day (task2 – task3)

a) Average RMS value

In this phase, it was obviously observed that, healthy subjects' RMS manifestation was almost the same as the last task in the first phase, with a very slight increase during this second phase, shifting from 122.7% - 123.7% (slope +1). For the elbow & wrist subjects, the value apparently turn to decrease inversely and significantly, by shifting from 162% - 157.7% (slope - 4.3). These may have represented a relatively slight recovery or less development of fatigue rate after the break on the healthy subjects, which was acting as a base line of this study. Meanwhile, the significant decrease, which had been observed in elbow & wrist MSDs subjects could have represented the lower muscle activation after the break, which may have been from whether some slight recovery or the adoption of muscle control and alternative movement strategy through the distribution of load via synergistic muscles (due to a result from the excessive shoulder muscle load during the previous phase). However, its value was still considered very high (157.7%) with respect to the other two cases.

On the other hand, in shoulder MSDs subjects, the RMS value still remained decreasing continually, with respect to the first phase from 129.7% - 121.3% (slope -8.4). This may have been interpreted as a result of the existing muscle fibre abnormalities over the histological and morphological changes, leading to the inability of handling with the task as normally occurring in the healthy ones. Therefore, in order to maintain the relatively same motor output as in the first task, this could have led to the adoption of muscle control and alternative movement strategy through the distribution of load via synergistic muscles as described previously on 7.1.1-a) the average RMS value of shoulder MSDs case (please review for more comprehensive detail), regardless of after having taken the 30 minute break. Namely shoulder part of these workers was still suffering the extreme fatigue and probably pain. Seemingly that, the 30 min break was not enough for regaining of the full recovery.

b) Average MDF value

For all cases, the values of averaged MDF were observed decreasing, but with different conditions. The value of MDF of the healthy and the elbow & wrist MSDs cases were observed in slightly less decreasing slope, compared with the first phase before the break, (34.4 Hz – 30.34 Hz (slope -4.06) and 28.6 Hz – 26 Hz (slope -2.6) for healthy and elbow & wrist MSDs case respectively, meanwhile, during the first phase: slope -5.3 and slope -10 were obtained from the healthy and elbow & wrist MSDs case respectively). This might be explained as the less fatigue development rate compared with the first phase (on the other hand, it was likely to regain some extremely small fatigue recovery). But this was still indicating a more fatigue sign even after the 30 min break. Therefore, it was likely that, the break could not help workers regain a full fatigue recovery, but likely help haling the fatigue development from constant occurring instead.

Anyways, the healthy case had a greater decreasing slope (-4.06), compared with the elbow & wrist one (-2.6), but the value from elbow & wrist case was in greater fatigue sign (28.6 Hz – 26 Hz) than in the healthy one (34.4 Hz - 30.34 Hz). This was in correspondence with what occurred in the RMS results, which could have been concluded as a result from the alteration of muscle control and alternative movement strategy, adopted over elbow & wrist portions, as same as the explanation on 7.1.2-a) the average RMS value of healthy, and elbow & wrist MSDs cases (please review for more comprehensive details).

However, for the shoulder MSDs subjects, the average MDF also decreased, but with the relatively greater slope than the other two, even by the time after the 30 min break. This was remarkably in line with the constant decrease remaining value of the average RMS over this period. Which in this specific case, it was showing the extreme fatigue and pain signs over the shoulder, based on the alteration of muscle control and alterative movement strategy, already explained in the previous section. Therefore, it could have been concluded as same as the one previously explained on 7.1.2-a) the average RMS value of shoulder MSDs cases (please review for more comprehensive details). Although the appearance of the adoption of an alteration of muscle control strategy over the shoulder, but due to its abnormality existing over the shoulder muscle fibre, therefore the fatigue and pain signs still remained and even being worse than the first phase.

c) Average local perceived discomfort

The healthy and elbow & wrist MSDs subjects had averaged local perceived discomfort remaining constant in this phase, with respect to the second task from the first phase (remaining at 1.67 (slope 0) and 1.0 (slope 0) for healthy and elbow & wrist case respectively). These were apparently corresponding to the results, obtained from either RMS or MDF parameter, that had showed a less fatigue development rate (on the other hand, it could be implied to a relatively slight recovery), via changing of value or slope toward the less sign of fatigue, compared with the first phase. However, they still remained showing sigh of accumulative fatigue, especially for the elbow & wrist case. By these, it might be able to conclude toward the influence of psychology issue, which probably caused workers to perceive overly in more comfortable feeling after the break, despite it was not observed much obviously in term of an objective issue as the physical EMG manifestation.

In one hand, the averaged local perceived discomfort, obtained from shoulder MSDs subjects, it had increased remarkably from 1.5 – 3.75 (slope +2.25), even after the break. This may have only been described as the result of existing shoulder muscle fibre abnormalities over the histological and morphological. This was in line with the results from either RMS or MDF parameter, showing more trend of pain and fatigue developing, which they were suffering overtime. Therefore, this may have represented the overwhelming feeling of the workers over the problematic muscle, being investigated via either objective or subjective issue. It was then likely that, the psychology issue may not have influenced the feeling of workers with shoulder MSDs, after the 30 minute break as same as in the other two cases, due to the extremely existing pain and fatigue over the area of investigation.

7.1.3 Third phase of the day (task3 – task4)

a) Averaged RMS value

In this phase, it was observed the healthy subjects' RMS value increasing overtime from 123.7% - 129.7% (slope +6), with greater increasing slope compared with in the second phase (slope +1). This may have been explained as the further more fatigue had been observed, which may have been according to the hypothesis of the additional MUs recruitment employment, previously described in the section of 7.1.1-a) the average RMS value of healthy case (please review for more comprehensive details). In addition, this could have been from a combined result of the fatigue accumulation, taking place thought out the day as demonstrating through the rising of the averaged RMS value overtime. Despite the intensity of the production was observed relatively lower than in the first phase during this measurement period. Therefore, this may have led to the smaller increasing slope (Slope +6), with respect to the first phase (slope +19).

For the shoulder MSDs case, the average RMS value apparently turned to increase inversely from 121.3% - 150.9% (slope +29.6). Which is considered as relatively high, and noticeably its final value (150.9%) was even higher than its starting one (135.1%) in the first phase, although they were also organized to work with relatively lower work intensity, with respect to the healthy ones during this period. This could have been explained as a result of the existence of the muscle fibre abnormalities over the shoulder, which may have been leading to the adoption of muscle control and alternative movement strategy, as described previously on 7.1.1-a) the average RMS value of shoulder MSDs case (please review for more comprehensive details), but in a different condition for this phase.

In this condition, it showed an increase of RMS value, which represented the more muscle activation occurring over the shoulder. This could have been explained as the result of the counteracting mechanisms (reversing effect) from the distributed synergistic muscles, having been deployed previously over the first and the second phase. They may have been already fatigued and developed some pain as well, thus it is likely that, those distributed synergistic muscles had also employed the adoption of muscle control and alternative movement strategy as a reversing consequence backward to the shoulder, forcing the shoulder desperately with no choice, by having to be allowed some more load handling backward from those (having already been fatigued from the two previous phases). Therefore, this may have led to the increase of RMS value observed over this phase.

For elbow & wrist subjects, the value still remained decreasing from 162% - 157.7% (slope -4.3), this may have been due to the possible two reasons. Firstly, the measure of the occupational and health affair, provided from the workplace, organizing all subjects with MSDs problem, whether elbow & wrist or shoulder MSDs case to work with relatively lower work intensity, with respect to the healthy ones during this period. On the other hand, they in fact were not able to cope with such regular production intensity for the all day long, as same as the healthy ones. By these, it may have caused the continuous trend of fatigue recovery sign, due to their existence of the healthy shoulder. Nevertheless, its value was still higher than the other two cases, which, this could have been explained as the result of the abnormality over the histological and morphological changes occurring over the elbow & wrist.

Consequently, this may have been forcing the shoulder to pay a critically major roll of task carrying, as previously explained in the section of 7.1.1-a) the average RMS value of elbow & wrist case (please review for more comprehensive details), therefore the relatively high accumulative fatigue still remained. Secondly since we had applied only one electrode arrays, measuring on the shoulder location, therefore, we couldn't exactly witness what was going on over the other distributed synergistic muscles. Thus, this sign of lower muscle activities after its peak, may probably have indicated the adoption of muscle control and alternative movement strategy over shoulder, having been already fatigued, and therefore may have been transformed into pain.

By this, it may have also employed an adoption of muscle control and alternative movement strategy, and consequently distributing load carrying to distributed synergistic muscles (probably backward the elbow & wrist portions), as the same way of the appearance of an increase of RMS value on the shoulder MSDs case over this phase.

b) Average MDF

The average MDF value of healthy subjects was observed decreasing overtime, but with smaller decreasing slope (30.34 Hz - 29.9 Hz; slope -0.44), compared with the two previous phases (with slope -5.3 and -4.06 for the first and the second phase respectively). This could have been explained as a further more fatigue being observed, as previously described in the section of 7.1.1-b) the average MDF value of healthy case (please review for more comprehensive details). However, for its smaller decreasing slope, this could have been as a result from the relatively lower production intensity, observed during the measurement, with respect to the previous two phases. However, along with the combination of the fatigue accumulation, obtained though out the day since the first task, this may contribute to the continuous decrease of MDF that still remained.

For the elbow & wrist subjects, the value of averaged MDF turned to increase inversely, shifting from 26 Hz – 35.8 Hz (slope +9.8). By this, it had demonstrated a significant fatigue recover. Therefore, it could have been a result from the outcome of the occupational and health affair measure, provided by the workplace, organizing all subjects with MSDs problem, whether elbow & wrist or shoulder MSDs case to work with relatively lower work intensity, with respect to the healthy ones during this period (phase), as previously mentioned. However, its ending value (35.8 Hz) was still lower than its beginning one (38.6 Hz), obtained from the first task of the day, this could have demonstrated the sign of a remaining accumulative fatigue.

Remarkably, subjects with elbow & wrist MSDs were with the shoulder considerably being healthy, therefore, this condition may have contributed to the efficient muscle recovery process developing over the period. However, since we didn't have EMG electrode arrays measuring on both elbow and wrist portions, it was then still unclear, whether what was going on inside those portions.

For the shoulder MSDs subjects, the MDF value still remained decreasing, from 27.3 Hz to 25.7 Hz (slope -1.6), with smaller decreasing slope, compared with the second phase (slope -6), this may have been a result of the measure of an occupational and health affair, provided by the workplace, organizing all subjects with MSDs problem to work with relatively lower production intensity, as previously described. However it was still observed quite obviously that, the ending value of 25.7 Hz was very low and even became the lowest one of all cases. By this, it still firmly indicated the relative extreme fatigue, severely remaining among the group of shoulder MSDs (as an affected muscle being measured by the surface EMG instrument), at the last phase of the day.

c) Averaged local perceived discomfort

The healthy subjects were observed an averaged local perceived discomfort increasing from 1.67 – 2.17 (slope +0.5). This represented the further suffering local perceived discomfort, which in line with the results obtained from either RMS or MDF value, that also showing the further more fatigue sign over the period. In addition, a psychology issue of the prolonged working may also contribute to this result, as it had entered into the last phase of the workday, despite the intensity of production was observed relatively lower than in the first phase.

For subjects with elbow & wrist MSDs, its averaged local perceived discomfort value was observed increasing along with the healthy one, ranging from 1.0 – 1.5 (slope +0.5). This could also have been explained as same as in the healthy subjects case, but for its lower value, this may have been from the influence of the psychology issue, involving with the existing fatigue and pain over their elbow & wrist, due to their muscle fibre abnormality. With this, it may have overly deviated their overwhelming feeling away from what was going on currently in their shoulder, where the surface EMG electrodes arrays, and local perceived discomfort were being measured.

For subjects with shoulder MSDs, its averaged local perceived discomfort value was observed increasing from 3.25 – 3.75 (slope 0.5), which was relatively higher than the other two cases. This was in correspondence with both RMS and MDF results, showing a further more fatigue sign, as already explained previously. In particular, this result could have well supported the hypothesis of the adoption of muscle control and alternative movement strategy as well as the counteracting mechanisms (reversing effect) among the affected shoulder and distributed synergistic muscles. Which may have distributed load carrying from shoulder to distributed synergistic muscles during the first and second phases, then the affected shoulder was forced with no choice to handle more load carrying backward over the last phase. Due to those distributed synergistic muscles were already fatigued and probably developing some pain, therefore they could also have adopted the muscle control and alternative movement strategy, counteracting mechanisms (reversing effect) of load carrying backward to the affected shoulder at last.

7.2 The ending period of Week-Day (Thu – Fri)

7.2.1 First phase of the day (task1 – task2)

a) Average RMS value

It was obviously observed from the healthy subjects that, its average RMS values started increasing from 108.8% - 113% (slope +4.2). In comparison with the same phase in the beginning Week-Day period (Mon - Wed), this starting value (108.8%) was pretty higher than in the previous one (103.7%), despite their tasks were performed at just the beginning phase of workday (no effect of any previous task on the same workday). This could have been concluded as the result of the accumulative fatigue, obtained over the beginning Week-Day period (Mon - Wed). Its increasing fatigue sign, indicated by the increasing slope overtime (+4.2) could have been explained based on the employment of an additional MUs recruitment, as same as in the section 7.1.1-a) the average RMS value of healthy case (please review for more comprehensive details).

For its relatively smaller increasing slope (slope +4.2), compared with the same phase in the beginning Week-Day period (Mon - Wed) (slope +19). This may have been due to the relatively low intensity of production over the period, observed during the EMG recording process particularly on Friday. Considerably, almost no production orders were processed during the third phase of Friday.

For the shoulder MSDs case, its averaged RMS value started at relatively high point, with the value as high as 171.7% before decreasing and ending up at 133.5% (slope -38.2). This could have been explained, based on the hypothesis of the adoption of muscle control and alternative movement strategy, as described previously on 7.1.1-a) the average RMS value of shoulder MSDs case (please review for more comprehensive details). And considerably, for its higher starting value (171.7%), compared with the same phase in the beginning Week-Day period (Mon – Wed) (135.1%), this may have been explained as a result of the accumulative fatigue and pain, obtained over the past beginning Week-Day period, which may have paid a key role for this higher starting value. Remarkably, for its greater decreasing slope (-38.2), with respect to the slope (-6.3) from the other beginning Week-Day period one, this may have been explained as the result of adopting alteration of muscle control and alternative movement strategy, as described previously on 7.1.1-a) the average RMS value section (please review for more comprehensive details). But with much higher rate of adaption

There was no case of the elbow & wrist MSDs, during this ending period of Week-Day, due to a non-match work shift among this case and the regular recording period.

b) Averaged MDF value

For the averaged MDF value, it was apparently observed that, the healthy subjects had had the starting value of MDF at very relatively low point (29.4 Hz), indicating a very high fatigue sign occurring, with respect to the same task over the same period but from the beginning period of Week-Day (Mon – Wed) (39.7 Hz). The timing of this fatigue sign is considered taking place very early, namely since the beginning period of the workday. This could have been explained as the result of the accumulative fatigue, obtained over the previous Week-Day period (Mon - Wed). Remarkably, it had occurred at very early likely even before the start of the first task of the day, despite the appearance of a relative lower production intensity of the production over this period. For its very relatively less decreasing slope (29.4 Hz – 29.2 Hz; slope -0.2), compared with the same phase of the beginning period of Week-Day (Mon - Wed) (39.7 Hz – 34.4 Hz; slope -5.3). This could have been as the result from the relatively low intensity of the production over this period, observed during the EMG recording process.

For the shoulder MSDs subjects, it was observed a decrease of averaged MDF value from 38 Hz – 25.5 Hz (slope -9). This slope was decreasing extremely sharp, with respect to the one obtained from the same phase of the beginning period of Week-Day (Mon - Wed) (34.5 Hz - 33.3 Hz; slope -1.2). This could have been explained as a result of the accumulative fatigue, gathering over the beginning period of Week-Day previously. Particularly, for its value on the second task (25.5 Hz), this is considered as a very extremely low, which was obviously lower than the values from either the healthy ones from the same phase of the same Week-Day period (29.2 Hz) or from the shoulder MSDs subjects over the same phase from the beginning period of Week-Day (33.3 Hz).

By this, it did indicate the badly extreme fatigue that those subjects were suffering, which may have been caused by the accumulative fatigue developed over the previous Week-Day period. This may have been contributed to a very early and quick fatigue development and seemingly with very severe effects. However, for its starting value (38 Hz), which was higher than the healthy ones from the same phase of the same Week-Day period (29.2 Hz), this may have been demonstrated the pretty efficient outcome of the counter measure of an occupational safety and health affair. Which was provided by the workplace, organizing all subjects with MSDs problem, whether elbow & wrist or shoulder MSDs case, to work with relatively lower work intensity, with respect to the healthy ones, during the third phase of the workday.

Although, its MDF value later ended up at very low level, and moreover with a very extreme decreasing slope (-9), however this counter measure may have already proved some benefit of its goals, by at least enhancing them to be more endurable for a longer capability against prolonged work across the long workweek. And even, it may have allowed the affected MSDs subjects to regain some small recovery among the Week-Day period, before encountering and suffering that fatigue and pain once again. Even though, this time (the ending period of Week-Day), it may come with the more severely suffering effects, as the time has passed by.

c) Average perceived fatigue

The healthy subjects were observed average perceived fatigue increasing from 1 – 1.14 (slope +0.14), slightly lower than in the same period from the beginning period of Week-Day (Mon - Wed) (1.33 – 1.67; slop +0.34). Its increasing slope indicates the more sign of fatigue developed overtime. For its less starting value as well as its less rate of increasing slope compared with the same phase from the beginning period of Week-Day, this was in line with a result from the averaged RMS value, which had been described as the appearance of a relative low intensity of the production over this period, observed during the EMG recording process. Although the result from the averaged MDF had shown sign of accumulative fatigue effect, taking place since the first phase of the workday.

By explaining this phenomenon, it could have been possibly that, the local perceived discomfort is more likely sensitive and complex to an individual subjective perception than the physical objective which is experiencing. Since this phase was in just the beginning of the workday, as well as its relative low intensity of production observed, these workers may have likely felt more comfortable by excessively than they were facing in term of the physical objective effect.

On the other hand, the shoulder MSDs workers were observed its averaged perceived fatigue decreasing from 4.0 - 3.0 (slope -1.0). Its starting value at 4.0 is considered as pretty high, before shifting down quite sharply to the level of 3.0, which was still higher than the value obtained from the same phase of the beginning period of Week-Day (1.25 - 1.5; slope +0.25). Its very high starting value may have reflected a perception of an accumulative fatigue and pain, gathering and occurring over the beginning period of Week-Day, which still remained in the subjects' perception. And according to the previous description of the appearance of the relative low intensity of production over the recording period, this may have had psychology effect, influencing the workers to feel more comfortable by excessively.

By this, it may have demonstrated through its inclination of the slope overtime, regardless of its RMS and MDF values, which still showing the existence of the more fatigue development. However, its value of the second task (3.0) was still high and even higher than the values of the same task from either the healthy subjects (1.14) (Ending period of Week-Day) or from the shoulder MSDs subjects (1.15) (Beginning period of Week-Day). This could have been explained as an effect of the accumulative fatigue and pain as well as the tiredness from the beginning period of Week-Day still remained affecting, although it was still in the beginning of the workday, in addition along with the appearance of the lower production intensity observed.

7.2.2 Second phase of the day (task2 – task3)

a) Averaged RMS value

For the healthy subjects, its averaged RMS value was observed decreasing after the break from 113% – 108.8% (slope -4.2), considerably pretty much lower than the result obtained over the same phase, from the beginning period of Week-Day (Mon - Wed) (122.7% – 123.7%; slope +1.0). This could have been as a result of the relatively low intensity of production over the ending period of week-day, observed during the EMG recording. And notably, with this relatively low production intensity, it may have been contributed to the obvious declination of RMS value after the break (slope -4.2), while on same phase of the beginning period of Week-Day (Mon - Wed), its value was slightly increasing with a slope of +1.0 (with more intensity of production).

For the shoulder MSDs subjects, it was observed its averaged RMS value still decreasing from 133.5% - 122.5% (slope -11). This could be explained, based on the explanation over the adoption of muscle control and alternative movement strategy, as described previously on 7.1.1-a) the average RMS value of shoulder MSDs case (please review for more comprehensive details). For its smaller declining slope, with respect to the result from the first phase of this Week-Day period (171.7% – 133.5%; slope -38.2), this may have indicated the appearance of less increasing fatigue and pain (presenting by its less decreasing slope) based on the previous mentioned hypothesis. Namely, with the relatively low intensity of the production over this Week-Day period, it appeared that, the 30 min break may have provided more efficiently beneficial outcome in regaining some evident fatigue recovery than being in the situation of high intensity production period as in the beginning of week-day.

This evidence was also in line with the result obtained from the healthy ones from this phase, showing some evidence of the more fatigue recovery than the result on the same phase from the beginning period of Week-Day.

b) Averaged MDF value

For healthy subjects, the averaged MDF value was observed decreasing after the break (29.2 Hz – 27.8 Hz; slope -1.4). In addition, it was also lower and having smaller declining slope than the value obtained from the same phase of the beginning period of Week-Day (34.4 Hz – 30.34 Hz; slope -4.06). Its lower averaged MDF value may have represented the accumulative fatigue, obtaining from gathering over the beginning period of Week-Day (Mon – Wed), nevertheless the appearance of lower intensity of production during this Week-Day period. However, with this appearance of lower intensity of production, it may have contributed to the lower sign of fatigue development via its lower decreasing slope (-1.4), compared with the same phase of the beginning period of Week-Day (-4.06).

For the shoulder MSDs case, its averaged MDF value appeared to remain steady after the break (slope 0), but remarkably, with as extremely low as 25.5 Hz, which became the lowest value off all cases. Compared with the healthy case (29.2 Hz – 27.8 Hz; slope -1.4), it was obviously demonstrated the more fatigue sign. And considerably, it was lower than the result obtained from the same phase in the beginning period of Week-Day (33.3 Hz – 27.3 Hz; slope -6). This may have indicated the accumulative fatigue effect, obtained over the (Mon – Wed) working period, in spite of its intensity of production was lower than in the beginning period of Week-Day. In addition, for the less decreasing slope (0 compares with -6), this may have represented the lower growing rate of fatigue development, due to the lower production intensity. Remarkably, its very low unchanged MDF value (25.5 Hz) may have indicated the extremely biological limitation of these affected shoulder MSDs workers in term of their critical situation (during the 3rd phase also unchanged).

c) Averaged local perceived discomfort

The healthy subjects case was observed the averaged perceived fatigue remained unchanged from 1.14 – 1.14 (slope 0) over the second phase. Noticeably, it was still lower than the result from the same phase of the beginning period of Week-Day (1.67 – 1.67; slope 0). This may have been as a result from the lower intensity of the production during this period of Week-Day, which may have had either physical or psychological influence over the perception of workers. Moreover, its unchanged value as well as its lower rising slope (0), compared with the result from the first phase (+0.14) may have shown some beneficial outcome of the midday break, in term of pausing their ongoing discomfort perception. In spite of, if consider the other EMG parameters on the same phase, the values from the MDF had shown more sign of some accumulative fatigue development, while the value from RMS had suggested the lower intensity of the production (lower amplitude).

For the shoulder MSDs case, the local perceived discomfort was also remained unchanged at 3.0 (slop 0), after decreasing down from the first phase (4.0 - 3.0; slope -1.0). This was in line with the appearance of the relative lower intensity of the production observed during this Week-Day period. Although, its steadily unchanged value at 3.0, however it was still considered as pretty high, and higher than the result from the healthy case on the same phase of this Week-Day period (1.4; slop 0). This may have indicated the effect of an abnormality, probably including fatigue and pain over the MSDs shoulder, as well as the accumulative fatigue gathered over the past Week-Day, which may badly have constantly overwhelmed the workers' perception.

7.2.3 Third phase of the day (task3 – task4)

a) Averaged RMS value

For the healthy subjects, its averaged RMS value was observed very slightly decreasing (108.8% – 108.7%; slope -0.1), with its development rate lower than in the first phase (108.8% - 113%; slope +4.2) and appearing to be very lower than the value of healthy subjects from the same phase of the beginning period of Week-Day (Mon – Wed) (123.7% - 129.7%; slope +6). This could have been explained as a sign of relative less fatigue development or could be a slightly fatigue recovery, which may having resulted from the relatively low intensity of production observed during the EMG recording, particularly over this phase (the last one of the workweek).

For the shoulder MSDs subjects, it was observed the extremely increasing value of averaged RMS from 122.5% - 165.7% (slope +43.2). This was in the same way of what had taken place on the shoulder MSDs one from the same phase of the beginning period of Week-Day (121.3% - 150.9%; slope +29.6), but this phase was with higher increasing slope. This could have been explained as a result of existing muscle fibre abnormalities over shoulder, leading to the adoption of muscle control and alternative movement strategy, as described previously on 7.1.1-a) the average RMS value of shoulder MSDs case (please review for more comprehensive details), but in a different condition for this phase.

In this condition, it showed an increase of RMS value, which represented the more sign of muscle activation occurring over the shoulder. This could have been explained as a result of the counteracting mechanisms (reversing effect) from the distributed synergistic muscles, having been deployed previously over the first and the second phase. Which those may have already been fatigued and developed some pain as well, thus it is likely becoming a reversing consequence backward to the shoulder, forcing the shoulder desperately with no choice, by having to be shared some load handling inversely backward from those ones, having been fatigued from the two previous phases. Therefore, this may have led to the increase of RMS value observed over this phase and making the whole developing graph became U-shape look. In addition, its higher ending value (165.7%) and higher increasing slope (+43.2) in this phase with respect to the result from the same phase of the beginning period of Week-Day (150.9% and +29.6 for ending value and increasing slope respectively), this may have been presented the greater fatigue and pain signs over the same phase from the beginning period of Week-Day.

In addition, if compare this with the healthy subjects from the same phase and the same Week-Day (108.8% – 108.7%; slope -0.1), which suggested the low intensity of the production. By this, it would have strongly supported the impact of the existing muscle fibre abnormalities of this case over the counteracting mechanisms (reversing effect) from the previously deployed synergistic muscles.

b) Averaged MDF value

For the healthy subjects, its averaged MDF value was observed increasing over this phase (27.8 Hz – 29; slope +1.2). This tendency indicated some fatigue recovery sign, which may have been a result from the relatively low intensity of the production particularly over this period (observed during the EMG recording). This was also in line with the result from the healthy averaged RMS (slightly decreasing; slope -0.1), observed on the same phase of the same Week-Day period described previously.

If consider the shifting range of MDF value over this whole Week-Day, it appeared just a little changing movement with a very narrow range from 29.4 Hz →29.2 Hz → 27.8 Hz → 29 Hz. respectively throughout the Week-Day. And if consider the shifting range of the MDF value over the whole beginning period of Week-Day, it showed a large movement by ranging from 39.7 Hz → 34.4 Hz → 30.4 Hz → 29.9 Hz respectively throughout the Week-Day. From these, it is remarkably that, this continuous decreasing slope over the entire week (Mon - Fri) could have demonstrated a fatigue development, and its accumulative fatigue throughout the entire week. In addition, the almost unchanged results of low MDF values over the ending period of Week-Day, this may have indicated the limit of workers ability against their physical endurance capability.

On the other hand, if considering the series of sequential Week-Days, the beginning (Mon-Wed) and the ending (Thu - Fri), there was a remarkable evidence that: the healthy workers was suffering the growing fatigue overtime throughout the entire week, particularly during the ending period one (Thu - Fri). However, after having had the rest over the weekend, they could apparently come back with a more or less completely fatigue recovery, as indicated by the starting value of the averaged MDF 39.7 Hz, at the first task of the beginning of Week-Day.

Unlike the shoulder and elbow & wrist MSDs cases, which it would be likely complicated to witness the uniformity of this fatigue development over the entire week, due to they were put in the measure of occupational safety and health during the workday, as an effort to enhance their endurance against their muscle abnormality, in order to be able to work through just a single workday, surviving as day by day. Therefore, their involving values may be seen fluctuating depending on their different individual conditions.

For shoulder MSDs subjects, it was observed a very slight increase of average MDF value from 25.5 Hz – 25.7 Hz (slope +0.2). This was indicating a slight fatigue recovery sign, which in line with the value from the healthy ones described above (slope +1.2). By this, it could be explained as the result from an appearance of the relative low intensity of the production over this period. Moreover, this was also in line with the value from RMS on the same phase of the same Week-Day, which was decreasing slightly (slope -1). However, considering its value compared with the result from the healthy one over this same phase and same Week-Day, it was still lower than the healthy one, and roughly becoming the lowest point of all cases and all times. This could just be explained as a result of their muscle abnormality, along with the accumulative fatigue gathering overtime since the beginning of the week. These may have contributed them to remain in the extreme sign of fatigue, despite the appearance of the relative low intensity of the production over this period.

c) Average local perceived discomfort

The healthy subjects were observed a slight increase of an averaged local perceived discomfort over this phase (1.14 – 1.29; slope +0.15). This indicated the more sign of slightly uncomfortable perception, which was in contrast with the results obtained from RMS and MDF, which showing signs of slightly fatigue recovery over the period. By this, it could be explained just as the result of the psychology effect, in term of prolonged working, due to it had already passed through the last phase of the ending Week-Day period (almost the whole week of working), despite the appearance of a relative low production observed over the period. Therefore, they might be perceiving like more uncomfortable overly. For its lower value and lower increasing slope compared with the result from the same phase on the beginning period of Week-Day (1.67 - 2.17; slope +0.5), this was indicating the less perceived fatigue sign, which could have been due to the relative lower production intensity over this period, which could have impacted both physical and psychological aspects.

For the shoulder MSDs subjects, its averaged local perceived discomfort was unchanged over this phase, namely remaining at 3.0 (slope 0) overtime. On the other hand, if compare with the value from RMS (122.5% - 165.7%; slope +43.2) and the value from MDF (25.5 Hz - 25.7 Hz; slope +0.2), which presenting a high level of muscle activity and very high level of a constant accumulative fatigue sign respectively. By these, it was likely that, the averaged local perceived discomfort (constant 3.0 which considered relatively high) was in line with the very high level of a constant accumulative fatigue sign and its sign of the counteracting mechanisms (reversing effect) from the distributed synergistic muscles, indicating by the rising RMS.

All these evidences along with its higher value with respect to the healthy case of this phase, therefore, it could have been explained as the result from the abnormality of MSDs over the shoulder that may have influenced the perception of this discomfort. Moreover, for its constant lower value (3.0) with respect to the first task (4.0), this may have been a result from the relatively low intensity of production over the period that might had influenced the perception psychologically, despite the appearance of the higher accumulative fatigue over this phase.

8 CONCLUSION

Working in real-world industrialized condition with heavily repetitive manual handling, those workers are seemingly put among a number of potential health threatening hazards. It is particularly for the work-related MSDs case, which is one of the most complex disorders, regarding to its wide range of symptoms possibly evidenced. The high-density surface EMG applied in this study, evidently came up with a performance of fatigue evaluation as well as the fatigue or muscle abnormality monitoring capability in advance. Noticeably, this study had also revealed some remarkable property of medical diagnosis-related behaviours over different participating cases, whether the healthy, shoulder MSDs and elbow & wrist MSDs case. Moreover, it was efficient even on the different various conditions, which clearly represent what are happening routinely in the industrial working conditions. Each particular case appeared to characterize differently depending on their medical-diagnosed condition as well as the difference in an occupational safety and health measure, provided specially to MSDs cases by the workplace.

The healthy workers appeared to be capable of dealing with the fatigue development pretty efficiently, although they were observed a gradual fatigue development over time throughout the day and week. Particularly, it was most highly evident at the ending period of Week-Day, demonstrating the occurrence of an accumulative fatigue. However, after the weekend rest, they were apparently able to come back with a fatigue recovery and resume their work as usual.

On the other hand, the MSDs cases either the shoulder MSDs or the elbow & wrist case, they was observed a huge difficulty in enduring against their routine duty for just only completing their entire single workday. The EMG results suggested that, they might have adopted an alteration of muscle control strategy over affected muscles, driven by nociceptive input to spinal and supraspinal circuitries. This could result in reducing of the descending drive to those muscles, contributing to the reduction on an activation of such muscle being in pain. Subsequently, this led to the restriction of movement over the painful muscles, and then apparently distributed most of the required motor output toward synergistic muscles instead. Accordingly, it is in line with the previous studies, investigating individuals with chronic LBP, which noticeably revealed a variety of biomechanical disturbances in various ways including: reducing acceleration of movement, decreasing velocity and restricting the range of motions.

By employing this biomechanical adaptation strategy, it could possibly be reflected by the unusual tendency of fatigue EMG manifestation. Namely, when the adoption of the alteration of muscle control strategy over such affected muscles taking place, the muscle activation (represented by RMS parameter) was observed going lower over the affected region, due to the excessive existence of the fatigue plus with the possibly growing pain, which had driven the shift of the active muscle fibres toward the synergistic muscles. Meanwhile, the accumulative fatigue sign (represented by MDF parameter) of that measured working muscle was still observed remaining in such severe affected level.

Once those option of imposed synergistic muscles had been also fatigued and possibly suffering some pain, they seemed to adopt an alteration of muscle control strategy as well, and then seemingly to return most of the required motor outputs backward to the measured muscles (shoulder), which had previously implemented the same strategy but inversely in the first place.

However, as this study had only one surface electrode arrays applying over the right shoulder, therefore it would not be completely clear for the EMG manifestation that could have occurred over the other imposed synergistic muscles or even in the other affected muscles such as elbow and wrist.

Considering the occupational safety and health measure provided by the workplace, those workers affected by MSDs either shoulder or elbow & wrist portion, they were managed to work with a relative lower production intensity during the second part of the workday. Consequently, it appeared that, this measure could help enhance their ability to endure such excessive heavily manual handling, however it was seemingly for just reaching the end of their single workday with desperately day by day effort. Otherwise, if without this, they may not be able to withstand such intensive working just for throughout the entire given workday alone, by not considering for over the whole weekday.

For the thirty minutes midday break provided by the workplace, it seemed not to be cable of helping those workers to regain such fatigue recovery. However, this management was likely to be able to pay off in a different term such as a psychological issue instead. Namely, their working muscles were still physically suffering fatigue and perhaps even a growing pain, but their perception was seemingly to sense more comfortable overly after the midday break.

With the pretty reasonable results, extracted from EMG raw signals, in the real working environment, this may have fairly well proved its potential performance. In addition, this research may have also revealed its overlooked significant function, which could have been utilized in the context of medical-related pre-diagnosis of such affected muscle portion. However, with this source of complexity in muscle fatigue evaluation, along with its required sophisticated technique and technology, this may need further more researches and developments in order to ensure this finding. Which, in one hand, it is absolutely our way as researchers to pursue this kind of endless scientific goals.

9 LIMITATION

According to the fact that, conducting the data collection in the real-world ongoing production line, it is certainly much more complicated than doing it in the experimental laboratory setting. There are possibly many uncontrollable conditions involving with the research. In this study, we were facing with many limitations as explained case by case as below.

- The machine operation failure:
  Sometime it restricted us to follow the sequential data recording time table that we had planned. And more importantly, it may have influenced to the result in term accumulative fatigue, due to the workers stopped working while the machine was being fixed.

- The missing of some subjects:
  The more longer scope of data collection, the more chance of having some subjects missing, it also happened with our data collection, due to we had scoped as long as the whole week of data collection. Accordingly, we also missed one case of Elbow & Wrist MSDs workers, due to their absence.

- The high level of uncontrollable set of movements:
  In the real time of production line, different workers often come with different strategy of movement, including different angle, speed and even some possibly instant problem that they have to solved at the time. Therefore, this had partially led to a practical method of using a long period and multiple average of the EMG parameter in signal analysis, which also corresponded to our intention to test its practicality.

- A few amount of cases study:
  This was particularly for the MSDs cases, whether the shoulder or Elbow & Wrist case, were found in the workplace. By this limit, it may have contributed to the less reliability of statistics analysis.

- The electrode montage recording configuration:
  Some may ask about the electrode montage configuration, since there are 2 available options between mono-polar and bi-polar. As this study is not an electrode montage efficiency comparison that may require the results of both for their performance, so in this research we utilized the monopolar configuration one. Regarding to there are a lot more suitable evidences than the bi-polar one in our particular case, which have already been mentioned in section 2.3.3.3. This is due to the fact that each configuration is designed to fit with different purposes of application.

10 PERSPECTIVE FUTUR RESEARCH

Regarding to this research, which its goals were mainly focused on the investigation of muscle fatigue development over either workday or workweek, as well as its correlation between the healthy and the subjects with different MSDs affected muscles (only upper limb). All results seemed to be reasonable and in line with many other recently found knowledges.

In addition, the research team also partially study some content that is likely a bit beyond our main focused scope that is focusing precisely at muscle fatigue. It is considered as a muscle activation that was evaluated through the movement of muscle activation centroid, which was calculated according to the studied intervals of all those muscle fatigue ones. Namely, the RMS values were averaged for each electrode location over all of 64 electrodes, which is so called topographical map.

The muscle activation evaluation was accomplished by calculating the centroid of topographical map, accordingly over each 60s of the muscle fatigue-focusing interval, throughout 300s of each task session as shown in figure 67. Afterward, they will be averaged into one final value, which could be representing the muscle activation centroid of each session.

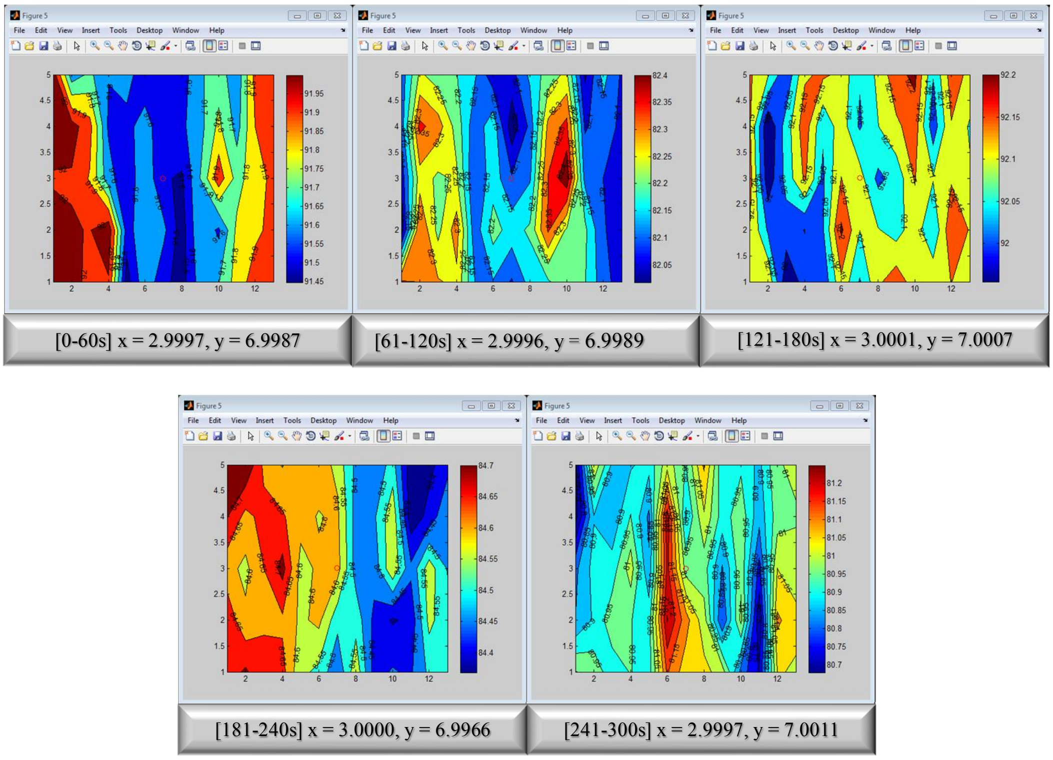

Figure 67. Muscle activation centroid of each topographical map, obtained from each consecutive 60s interval over 300s of one task session

By plotting the x-coordinate and y-coordinate of each session and each case study into a form of 2-D graph, we found that there was a movement of muscle activation centroid accompanying with the running session throughout a workday and weekday as can be demonstrated in figure 68.

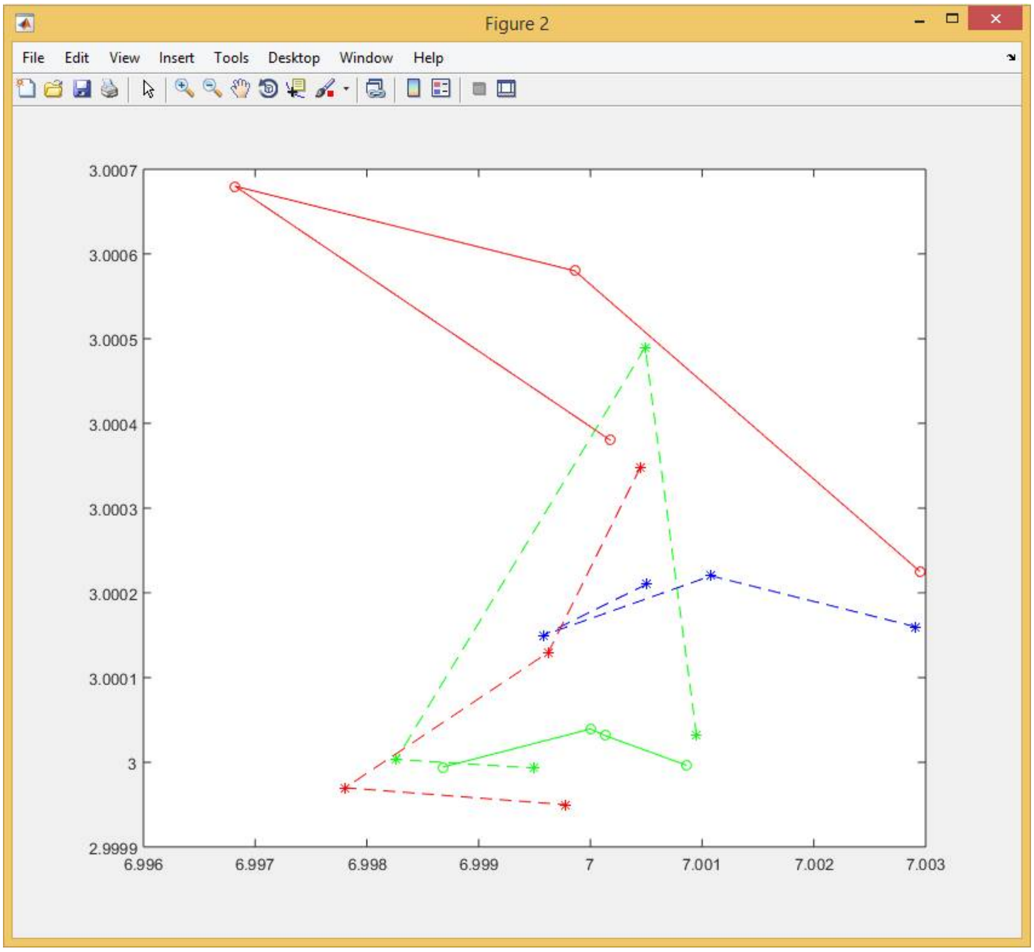

Figure 68. The movement of muscle activation centroid of each case study over each session throughout a workday and weekday.

Where:

(For the type of line)

------ Represents the beginning period of weekday (Mon-Wed)

—— Represents the ending period of weekday (Thu – Fri)

(For the colour)

Green: represents the healthy subject

Brue: represents the elbow & wrist MSDs subject

Red: represents the shoulder MSDs subject

10.1 Associated current finding

According to this finding, it is also in line with many studies concluding that there is a movement of muscle activity centroid, believed to avoid muscle overloading on the same location that may cause a severe injury. Which on the other hand, it is likely the strategy to handle the prolonged muscle contraction task by sharing muscle worked load toward other areas according to the ongoing physical load.

By utilizing this theory, it is then possible to explain well the movement of the healthy case. Namely, during the beginning of weekday, all healthy workers seem to potentially have the ability of distributing muscle loading to other locations throughout the workday. Anyways, when the time passed by, they seemed to have a restriction of the muscle load distribution, as seen as the relatively smaller movement area during the ending period of weekday, as demonstrated in figure 68.

Considering the found different moving direction of the muscle activation centroid, it was likely that each case study tent to have their own moving pattern. This

Anyways, as this research involved with so complex MSDs cases, including Shoulder, elbow and wrist effect, which in some cases they were suffering with more than one MSDs condition. These may lead to a complicated implication. This may have been due to the fact that individual may have the same amount of fatigue but different moving direction of the muscle activation centroid, which depends on so many factors as already mentioned above.

10.2 Interesting issue for future research

Based on this associated current finding discovered by this research, it is interesting to keep the research trend toward the feasibility of distinguishing subjects with different muscle condition, which could be identified by the movement of muscle activation centroid. Since, those affected cases seem to move with different strategy, by minimizing as much painful muscle as possible, from the healthy one.

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12 APPENDIX

12.1 Instrument specification

User manual v 2.0

EMG-USB2

Multichannel Bioelectrical Signal Amplifier

⚠ **Read this manual carefully before using the EMG-USB2 amplifier.**

CE

This product is manufactured in compliance with the European Standard 93/42/CEE about medical instrumentation, and according to the EN 60601 rules for Medical Electrical Equipment

6. TECHNICAL SPECIFICATIONS

EMG-USB2 is an optically and galvanically insulated device designed to guarantee a high safety level for the patient and the operator in all operating conditions. The optical and galvanic insulation separates the circuitry connected to the patient from the circuitry connected to external non-medical devices, such as the PC used for data acquisition and user interface. An embedded circuitry, called Driven Right Leg (DRL) circuitry, is available to reduce common mode voltage noise arising from electrical interference from the power line. The DRL is particularly useful in monopolar acquisition mode.

Table 1 shows an example of possible probes configurations with the available versions of the EMG-USB2.

Device configuration	Example of probes configuration
256 channels	four 16 channel probes and three 64 channel probes
128 channels	four 16 channel probes and one 64 channel probe
64 channels	four 16 channel probes
16 channels	one 16 channel probe

TAB. 1: *Examples of probes configurations with EMG-USB2 amplifier.*

As shown in the examples, it is possible to simultaneously acquire signals with different probes. This is necessary when signals from different muscles need to be recorded at the same time or when EEG and EMG has to be recorded together.

Using the front panel keypad, it is possible to assign a gain value to each probe. When the signals are detected from different sources, it can be necessary to set different gain levels for each probe to exploit the full range of the A/D converter and obtain the best possible recording of the signal.

EMG-USB2 technical specifications are shown in TAB. 2.

Amplification channels (IN1÷4 and MULTIPLE IN 1÷3)	
Selectable gain	OFF, 100, 200, 500, 1000, 2000, 5000, 10000 V/V
Selectable bandwidth	High pass filter: 3, 10, 100, 200 Hz Low pass filter: 130, 500, 900, 4400Hz
Maximum input range	50 mV_{PP}
Noise level referred to input	< 4 μV_{RMS}
Input impedance	> 10^{11} Ω
CMRR	> 95 dB
Output range	0 ÷ 5 V
Insulation voltage	4.000 V_{DC}
Auxiliary channels (AUX-IN 1÷16)	
Input range	± 5 V
Bandwidth	Channels are not filtered
Gain	0.5 V/V
Input impedance	200 kΩ
A/D converter input dynamics	0 ÷ 5 V
Data conversion	
A/D converter resolution	12 bit
Data transfer to PC	USB2 interface
Selectable sample frequency	512, 2048, 4096, 10240 Hz

TAB. 2: *EMG-USB2 technical specification*

8. USE OF EMG-USB2

EMG-USB2 CONFIGURATION

The embedded keypad and the display on the front panel of EMG-USB2, allow the operator to change the settings of the amplifier as explained in the following instructions:

- Using PREV. INPUT ◀ and NEXT INPUT ▶ keys it is possible to browse the inputs menu.
- Move the selection to the desired parameter using ▲ and ▼ keys.
- Press OK to confirm the parameter selection; only the parameter will be negative displayed to indicate that it is possible to change the value of the selected parameter.
- Scroll the available options and select the desired value using the ◀ and ▶ keys.
- Press OK to confirm the new value.

Selecting the option *Enter Set-Up* the instrument give access to the Set-Up menu where it is possible to set additional parameters.
All the settings are send to the PC at the end of each acquisition and the settings are stored together with the signals by OT BioLab. For further details refer to the OT BioLab user manual.
When the EMG-USB2 is switched off the settings are stored into an internal memory and are reloaded when the instrument is switched on again.
A complete description of the parameters and settings can be found in the following sections.

Detection Mode

EMG-USB2 feature different detection modalities. The detection mode is displayed in the first line of every input menu and is common to all the amplifier channels. In table 3 are listed and described all the available options. To better understand how the different mode works, it is important to remember that each input of the amplifier manages 16 signals (in case of IN 1÷4) or 64 signals (in case of MULTIPLE IN 1÷3) from the adapters. Each channel amplify the difference between two signals.

Parameter	Available options	Description
MODE	Chained Diff.	It is a single differential mode. Each channel amplify the difference between a subsequent signals of each input . The last channel of each input is obtained as difference between the last signal of the same input and the first signal of the subsequent input. For example, in this mode, the channel 16 is obtained as difference between the signal 16 (last signal of IN 1) and the signal 17 (first signal of IN 2). This mode have to be used when connecting an electrode matrix or an array to several input.
	Looped Diff.	It is a single differential mode. Each channel amplify the difference between a signal and the subsequent one. The last channel of each input is obtained as difference between the last signal and the first signal of the same input. For example, in this mode, the channel 16 is obtained as difference between the signal 16 (last signal of IN 1) and the signal 1 (first signal of IN 1). This mode have to be used when connecting a rectal probe.
	Float. Monop.	All the channel makes the difference between the corresponding input signal and the signal at the *DRL IN* connector. The DRL IN must be connected, by means of a ground strip to a point on the body patient without bioelectrica activity. This is a monopolar detection since all the channels are referred to the same potential present at DRL IN. This mode can be used with standard adapters to detect signals in monopolar mode.
	Refer. Monop.	All the channel makes the difference between the corresponding input signal and the reference point of the amplifier. This mode can be used jointly with adapter with suffix M5. This kind of adapters are specially designed to reduce interferences in monopolar detection.
	Bipolar	This modality require special adapters that allow the signals detection from electrode pairs as standard bipolar EMG.
	Hybrid	This mode can be used when different type of adapters are used together. In this condition the detection mode in not forced by the instrument but depend on the type of adapter used.

TAB. 3: *Detection mode details*

Amplification Gain

The amplification gain for each input can be set by the user. Indication of the gain settings are displayed at the second line of every input menu. The gain by default can be different for each amplifier input. Browsing the different input menus, by means of ◀ and NEXT INPUT ▶ keys, it is possible to see all the different gains. PREV. INPUT

Activating the *Global Settings* configuration (Refer to the Set-Up menu), the gain of all inputs is force to be equal. In this case, browsing the different input menus, all the input will display the same gain value than can be modified in any input menu.

In table 4 are listed all the available gains.

Parameter	Available options	Description
GAIN	OFF	The corresponding input is turned OFF
	100	All the signals related to the corresponding input are amplified by respective the factor. In case of EMG recordings lower values can be used during high level contractions or during electrically elicited contractions. Higher values are suggested when recording from deep muscles or during low level contractions.
	200	
	500	
	1.000	
	2.000	
	5.000	
	10.000	

TAB. 4: *Amplification gain description*

High pass and Low pass filters

The bandwidth for each input can be set by the user. Indication of the filters settings are displayed at the third and fourth line of every input menu. The filters by default can be different for each amplifier input. Browsing the different input menus, by means of PREV. INPUT ◀ and NEXT INPUT ▶ keys, it is possible to see all the different cut off frequencies.

Activating the *Global Settings* configuration (Refer to the Set-Up menu), the cut off frequencies of all inputs are force to be equal. In this case, browsing the different input menus, all the input will display the same High pass and Low pass values than can be modified in any input menu.

In table 5 are listed all the available cut off frequencies.

Parameter	Available options	Description
HP Filter	3 Hz	All the signals related to the corresponding input are high pass filtered and low pass filtered with the 3 dB cut off frequency displayed. It is up to the user to select the correct filters value for the conditioning of the desired signals. OT BioLab, in any case provide a warning when the cut off frequencies do not respect standard values for a given type of signal. Refer to the OT BioLab user manual for further details.
	10 Hz	
	100 Hz	
	200 Hz	
LP Filter	130 Hz	
	500 Hz	
	900 Hz	
	4.4 kHz	

TAB. 5: *Selectable filters description*

Analog out setting

The EMG-USB2 features an analog output (refer to the details of the rear panel of the instrument) where can be sent one of the signals filtered and amplified by the available channels. This signal is internally sampled at 10240 Hz and converted in digital form, cross the insulation barrier and then is re-converted in an analog signal. The output of the digital to analog converter is filtered with a 4100 Hz low pass first order filter to remove the staircase shape on the output signal.

The user can choose the channel to be sent at the analog output from any Input menus.

⚠ **REMARK: even if any of the 256 channels can be selected, only the signals sent to the PC through the USB (refer to the OT BioLab manual) are useful signals. A flat line is generated by the analog output when a channel not sent to the PC is selected.**

Global Settings

To simplify the gains and filters setting, it is possible to force the gain, high pass filters and low pass filters to be equal across all inputs. This can be done entering in the Set-Up menu and then modifying the *Global Settings* in the ON condition. When the *Global Settings* is activated it is possible to modify the parameter from any input menu and the changes will be applied to any other input.

PATIENT CONNECTION

After the correct installation of the electromyograph and after verifying that it works properly, it is possible to connect the sensors to patient in order to perform a biopotential recording. Follow the instructions listed below:

- For each input, select the suitable adapter for the measurement to perform and plug it into one of the the *IN* or *MULTIPLE IN* connectors.
- Connect the adapters, the electrodes arrays or matrix, the wires or needles or standard electrode suitable for the desired application.
- Connect a patient ground strip to *PATIENT REF* plug with the enclosed cable. The strip has to be wet with water to assure a good electric contact with the patient and has to be connected on a point without any bioelectrical activity (e.g. the ankle or the wrist, FIG. 6).

⚠ **REMARK: the lack of this connection prevents the correct acquisition of the EMG signal.**

Figures 6, 7, 8 and 9 show some connections example to acquirebioelectrical signals in different modalities available using EMG-USB2.

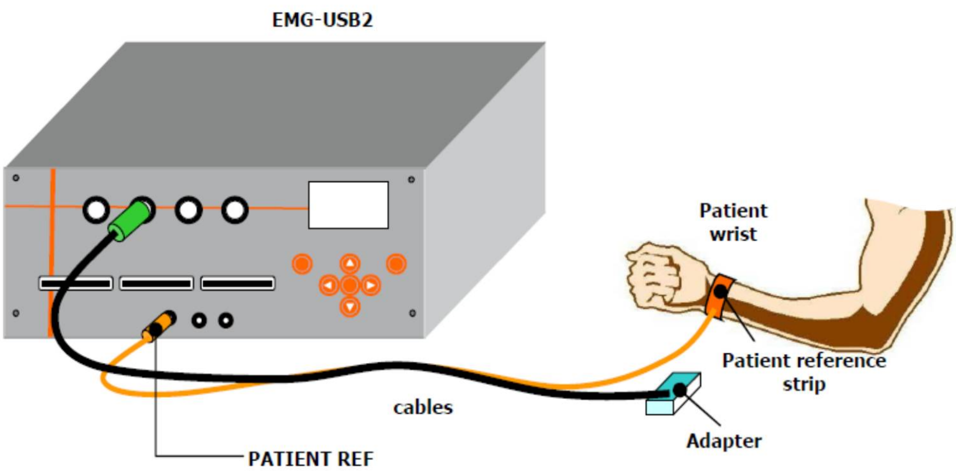


FIG. 6: *Patient connection diagram for signal acquisition in differential modalities*

(Mode: Chained Diff. or Looped Diff.)

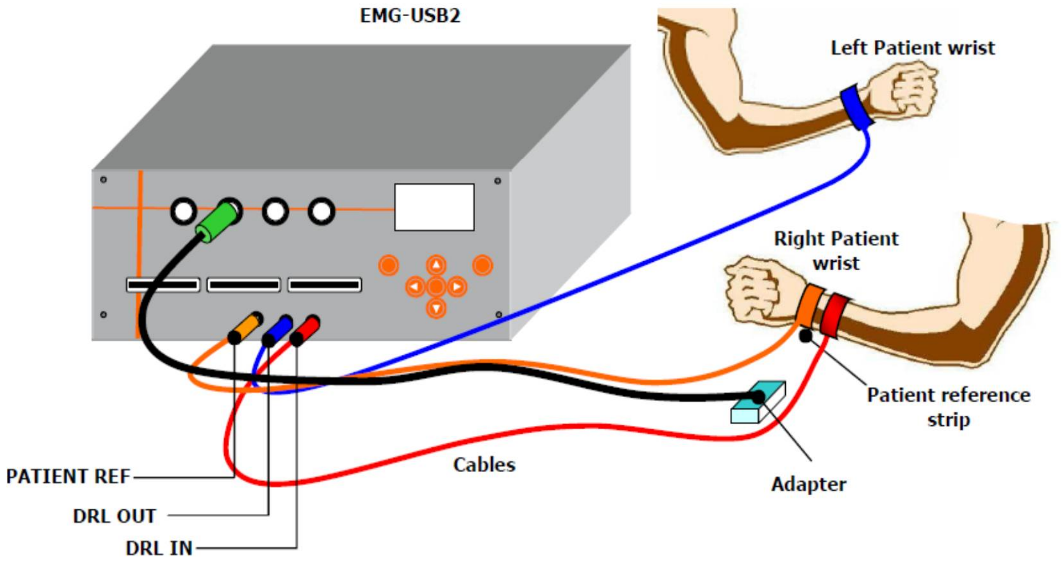


FIG. 7: Patient connection diagram for signal acquisition in floating monopolar modality
(`Mode: Float. Monop.`).

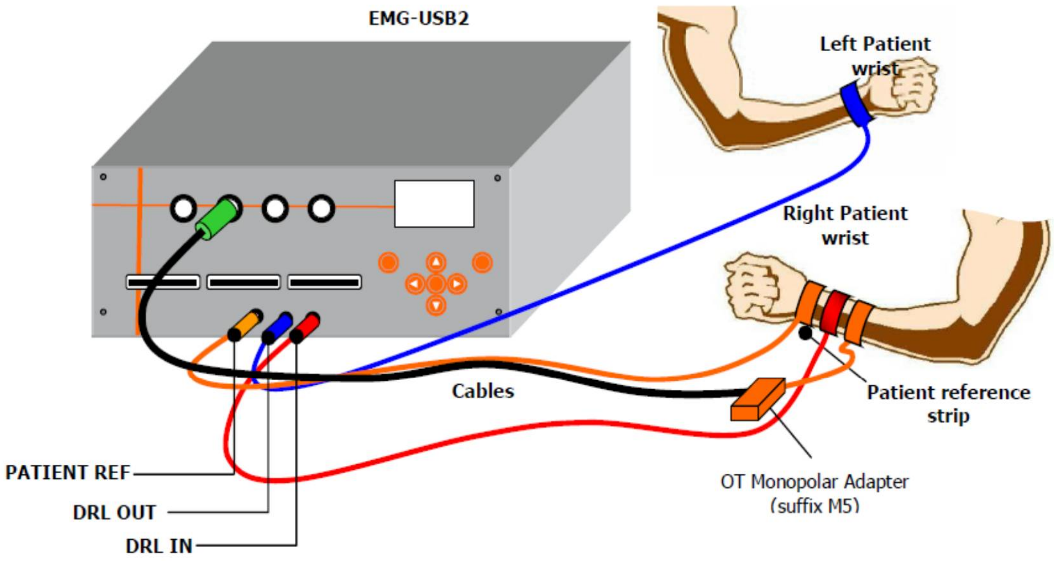


FIG. 8: Patient connection diagram for signal acquisition in referred monopolar modality
(`Mode: Refer. Monop.`).

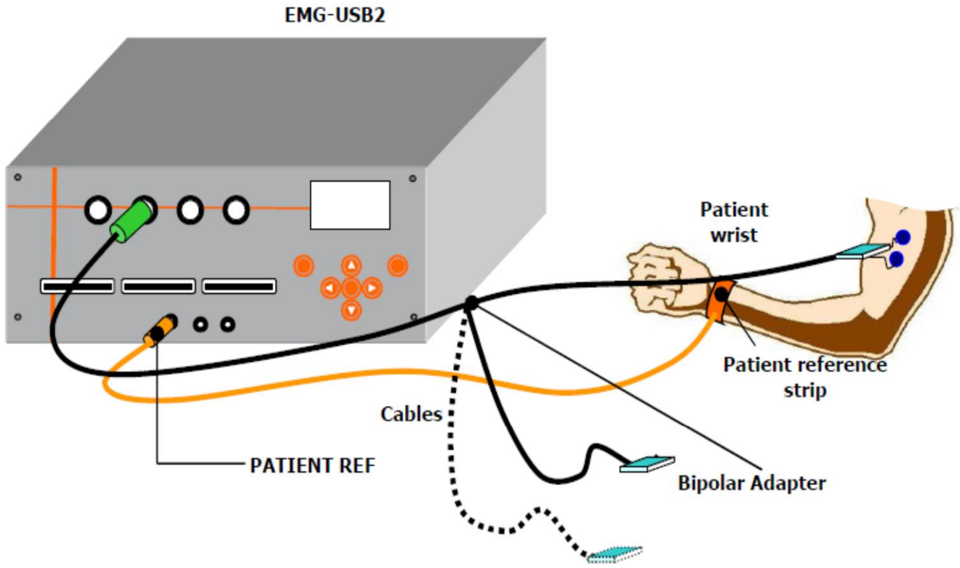
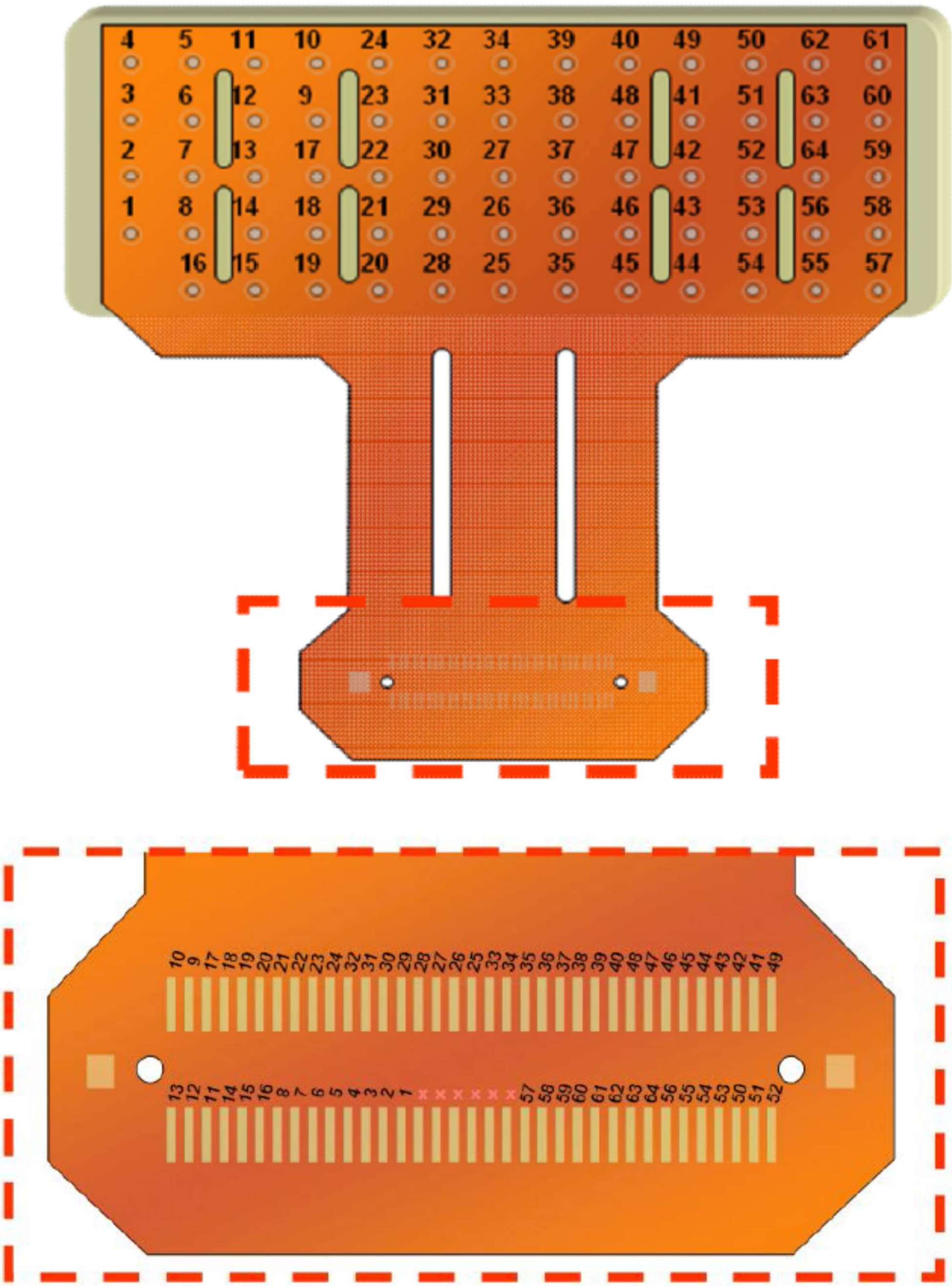


FIG. 9: *Patient connection diagram for signal acquisition in bipolar modality*
(`Mode: Bipolar`).

12.2 Sensor 64 array electrode

ADHESIVE MATRIX ELSCH064NM2 Pin Out

(Posterior View)



MATRIX 64 Ch ELSCH064NM2 ied 8 mm

12.3 Informed consent form

1

U.PORTO

Doctoral Program of Occupational Safety and Health

Declaration of Informed Consent

(Base on Annex A of ISO 12894:2001)

Name...

Gender: ❑ Male ❑ Female

Date of birth ....

Medical assistance...

Residence..

The declaration of all intents and purposes:

1) I am willing to participate as volunteer in this experimental study on the topic: "Assessment of Muscle Fatigue in Work Related Musculoskeletal disorders by using High-Density Surface EMG" to be conducted by a research team of the Faculty of Engineering (FEUP) and Faculty of Medicine (FMUP), University of Porto, under the Doctoral Program of Occupational Safety and Health (DemSSO), Faculty of Engineering.

2) I have received an explanation of the comprehensive details and purposes of this study and any risks to my health that could be:
- There is the possibility to have an irritation or discomfort over the sensor contacted skin's area.

3) I agree to provide accurate information about my health and ongoing medical examination if this is necessary. I agree to allow my personal doctor to provide information about my historical medical treatment to the authorized doctor of this study. I understand that all information about my health will be attentively treated in confidence.

4) I agree to fully cooperate with investigators and promise not to take any voluntary action that may invalidate the results.

5) During the period of investigations that I am now giving my consent, I promise not to participate as volunteer in any other study, without previously informed to the researchers of this research project and having obtained its approval afterward.

6) I know I am free to withdraw my consent of participation in the study at anytime, without the necessity of giving an explanation for my decision.

7) I allow all data obtained from my body to be used for the production of research articles and I know that my identity will be kept secret at any processes.

Signature .... Date ....

2

U. PORTO

Doctoral Program of Occupational Safety and Health

Declaration of the researcher

Within the study described above, the research team has explained. ....The comprehensive detail and purposes of the study and possible risks of the participation. Nevertheless the decision of the volunteer is not involved with the right of compensation in case of illness or injury, which might have been occurred during or after the data collection.

Signature .... Date ....

12.4 Questionnaire form

U. PORTO

Doctoral Program of Occupational Safety and Health

Questionnaires

1. Personal information (Please complete or tick ☑ all these questions)

1.1) Date completed: ……………………………………

1.1) Subject's name: ……………………………………………………………………………………..

1.2) Gender:
❑ Male ❑ Female

1.3) Date of birth : …………………………………………, Age……………….

1.4) Weigh…………….kg, High..................cm

1.5) Dominant hand side :
❑ Left ❑ Right

2. Working experience

2.1) Department……………………………………………………………………………………..

2.2) What kind of your job……………………………………………………………………………..

2.3) How long have you been working in this department ……………………………………………

2.4) How many hours do you perform work task a day……….…….
Starting time …………......... Ending time………………………

3. Fatigue or tiredness history

3.1) Do you have any diagnosed medical conditions related to musculoskeletal disorder?❑No ❑Yes

☑ If you replied "**Yes**" please complete following questions ; a) and b)

a) What body part is your problem?...
b) How long have you been suffered? ………………………………………

3.2) Are you currently experiencing any problems with fatigue or tiredness? ❑ No ❑Yes

☑ If you replied "**Yes**" please complete following questions; a) and b)

a) When has your fatigue begun? (check one):

❑ Rapidly - within 24 hours ❑ Over 1 week
❑ Over 1 month ❑ Over 2-6 months
❑ Over 7-12 months ❑ Over 1-2 years
❑ Longer than 2 year ❑ had problems with fatigue since childhood or adolescence

b) What do you think the cause of your fatigue is mainly from?
❑ household related activities ❑ social-related activities ❑ work-related activities

4. Experimental fatigue experienced

Do you feel any fatigue on the following body area R, P, T, S shown in the body diagram over working hours? Please specify the level of fatigue by selecting the provided scales.

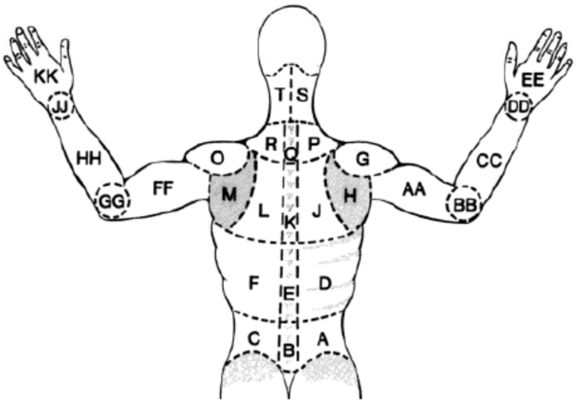


Figure 1. Local perceived discomfort method body-diagram

Table 1. The score of perceived discomfort : Please mark "X" in each session with the score of discomfort you are perceiving.

Discomfort score	Before				1st session				2nd session				3rd session				4th session			
	R	P	S	T	R	P	S	T	R	P	S	T	R	P	S	T	R	P	S	T
[0] Nothing at all																				
[1] Very weak (just noticeable)																				
[2] Weak (light)																				
[3] Moderate																				
[4] Somewhat strong																				
[5] Strong (heavy)																				
[6]																				
[7] Very strong																				
[8]																				
[9]																				
[10] Extremely strong																				

12.5 MATLAB operating codes

12.5.1 Normalization M-file

```
clear all;
close all;
clc;

%% Loads the file
[filename, pathname] = uigetfile('*.sig', 'Pick an .otb file');

clear filterindex
filename2 = strtok(filename,'.');

if ~exist([pathname filename2 '.sig'],'file')
  unzip([pathname filename], pathname)
  [Data, SamplingFrequency, Time] = aprisigfile([pathname filename2
'.sig']);
  save([pathname filename2], 'Data', 'SamplingFrequency', 'Time');
elseif ~exist([pathname filename2 '.mat'],'file')
  [Data, SamplingFrequency, Time] = aprisigfile([pathname filename2
'.sig']);
  save([pathname filename2], 'Data', 'SamplingFrequency', 'Time');
else
  load([pathname filename2 '.mat']);
end

% 8 channel matrix mapping by column (SD)
Col{1} = [4,5 ,11,10,24,32,34,39,40,49,50,62,61];          % column no.1
Col{2} = [3,6 ,12,9 ,23,31,33,38,48,41,51,63,60];          % column no.2
Col{3} = [2,7 ,13,17,22,30,27,37,47,42,52,64,59];          % column no.3
col{4} = [1,8 ,14,18,21,29,26,36,46,43,53,56,58];          % column no.4
col{5} = [1,16,15,19,20,28,25,35,45,44,54,55,57];          % column no.5
n_column = 5;

%-----------------------------------------

%% Common variables

% Filter of EMG signals by digital procedure
[be ae] = butter(2,[10/(SamplingFrequency/2) 500/(SamplingFrequency/2)]);
% coefs
gain    = 5000;
% filter gain


%% Crops the file to the interval between t1 and t2 (the interval of a
recorded standard isometric test contraction)

t1 = 0.05; % in seconds
t2 = 29; % in seconds
% determines the samples to crop
sample_init = SamplingFrequency * t1; % start
sample_end  = SamplingFrequency * t2; % end
```

```
Data_cropped = Data(sample_init:sample_end,:);
Time_cropped = Time(sample_init:sample_end); % time vector is also
updated


%% Calculates the RMS value for each electrode => entire signal is used!

matrMAX    = zeros(size(col{1},2),size(col,2));

DataAbs    = abs(Data_cropped(:,:)); % takes absolute value

for column = 1 : n_column
    for row = 1 : length(col{column})

        SigMON1 = DataAbs(:,col{column}(row));
        SigMON= filtfilt(be,ae,SigMON1)./2^12.*10./gain.*1000000;

        % UNCOMMENT NEXT LINE FOR RMS VALUES
        MAX_mon = sqrt(sum(SigMON.^2)/length(SigMON));

        matrMAX(row, column) = MAX_mon; % stores into max matrix

    end
    end

clear DataAbs i column row SigMON1 SigMON MAX_mon % deletes aux variables
clear Data_cropped Time_cropped ae be col gain n_column
```

12.5.2 Dynamic-task session M-file

```
% DO NOT DO CLEAR ALL! matrMAX VARIABLE IS NEEDED TO RUN THIS SCRIPT!!

close all;
clc;

%% Loads the file
[filename, pathname] = uigetfile('*.sig', 'Pick an .otb file');

clear filterindex
filename2 = strtok(filename,'.');

if ~exist([pathname filename2 '.sig'],'file')
  unzip([pathname filename], pathname)
  [Data, SamplingFrequency, Time] = aprisigfile([pathname filename2
'.sig']);
  save([pathname filename2], 'Data', 'SamplingFrequency', 'Time');
elseif ~exist([pathname filename2 '.mat'],'file')
  [Data, SamplingFrequency, Time] = aprisigfile([pathname filename2
'.sig']);
  save([pathname filename2], 'Data', 'SamplingFrequency', 'Time');
else
  load([pathname filename2 '.mat']);
end

% 8 channel matrix mapping by column (SD)
Col{1} = [4,5 ,11,10,24,32,34,39,40,49,50,62,61];           % column no.1
Col{2} = [3,6 ,12,9 ,23,31,33,38,48,41,51,63,60];           % column no.2
Col{3} = [2,7 ,13,17,22,30,27,37,47,42,52,64,59];           % column no.3
col{4} = [1,8 ,14,18,21,29,26,36,46,43,53,56,58];           % column no.4
col{5} = [1,16,15,19,20,28,25,35,45,44,54,55,57];           % column no.5
n_column = 5;

%-----------------------------------------

%% Common variables

% Filter for EMG
[be ae] = butter(2,[10/(SamplingFrequency/2) 500/(SamplingFrequency/2)]);
% coefs
gain    = 5000;



%% Crops the file to the interval between t1 and t2 (the interval of the
considered each consecutive 60s epoch across 300s dynamic task sessions)

t1 = 240; % in seconds (varying following the consecutively considered
epochs)
t2 = 290; % in seconds (varying following the consecutively considered
epochs)
% determining the samples to crop
sample_init = SamplingFrequency * t1; % start
sample_end  = SamplingFrequency * t2; % end
```

```
Data_cropped_1 = Data(sample_init:sample_end,:);
Time_cropped_1 = Time(sample_init:sample_end); % time vector is also
updated

%clear t1 t2 sample_init sample_end % deletes a3ux variables


%% 200ms window code section starts here

interval   = 0.2; % duration of the interval for analysis in seconds

window_size = interval * SamplingFrequency;

index = 1;

for i = 1:window_size:length(Data_cropped_1)-window_size-1

    Data2 = abs(Data_cropped_1(round(i:i+window_size-1),:));
    len = length(Data2);

    for column = 1 : n_column
        for row = 1 : length(col{column})
            %% Calculate RMS value
            SigMON2 = Data2(:,col{column}(row));
            SigMONa = filtfilt(be,ae,SigMON2)./2^12.*10./gain.*1000000;
            RMS_matrix{index}(row,column) = sqrt(sum(SigMONa.^2)/len) /
matrMAX(row,column) * 100;


        end
    end

    index = index+1;

end

%% plots RMS value

toPlot = 1;
if toPlot

    rms_vecs = [];

    for column = 1 : n_column
        for row = 1 : length(col{column})
            aux = [];
            for j = 1:length(RMS_matrix)
                aux = [ aux RMS_matrix{j}(row,column) ];
            end

            rms_vecs = [rms_vecs ; aux];
        end
    end
    %% Calculate mean value from length of considered epoch
length(RMS_matrix)-1
```

```
    %% calculate mean value from 65 columns
    rms_vecs_t = rms_vecs.';
    avg_RMS_65 = mean(rms_vecs_t);
    fprintf(' Average-RMS(each electrode) = ............... %2.3f
\n',avg_RMS_65);

    avg_RMS = mean(avg_RMS_65);
    fprintf('*** Overal average-RMS = ............... %2.3f \n',avg_RMS);

    t = [0:0.2:0.2*(length(RMS_matrix)-1)];

    % Plot rms against time (t)
    plot(t,rms_vecs);
    xlabel('Time [s]');
    ylabel('Amplitude [%]');
    grid on
end


%% neighbour subtraction
for column = 1 : n_column
for row = 1 : length(col{column})
    matrDATA{row,column} = Data_cropped_1(:,col{column}(row));
end
end

 %% frequency calculations start here - FFT
    T = 1/SamplingFrequency; % period
    medianfreq = cell(length(col{1}),n_column);
    medianfreq1 = cell(length(col{1}),n_column);
for column = 1 : n_column
        for row = 1 : length(col{column})
            L = length(Data_cropped_1);
            t = (0:L-1)*T;

                % MDF with Welch method calculation
                n_t = numel(t);
                seg_lth=500; % segment length
                ovl_per=50; % 50 % of overlap
                Hs = spectrum.welch('Hamming',seg_lth,ovl_per);

psd_welch=psd(Hs,matrDATA{row,column},'Fs',SamplingFrequency/2,'NFFT',n_t
,'SpectrumType','onesided'); % Hs : method (Welch)
                normcumsumpsd =
cumsum(psd_welch.Data)./sum(psd_welch.Data);
                Ind = find(normcumsumpsd <=0.5,1,'last');
                medianfreq1{row,column} = psd_welch.Frequencies(Ind);

                disp(['Column ', num2str(column),' : row ',
num2str(row)]);
                fprintf('Median frequency Welch method is %2.3f
Hz\n',psd_welch.Frequencies(Ind));

                %figure();
                %plot(psd_welch);


        end
```

```
end


                  %Calculate averaged MDF value across all electrode grids
                  and its output presentation

                  MDF_vector = [];
                  for column = 1:n_column
                  for row = 1:length(col{column})
                  k = [];
                  k = [k medianfreq1(row, column)]
                  MDF_vector = [MDF_vector k];
                  end
                  end
                  Avg_medianfreq1 = mean(MDF_vector);



                  fprintf('*** Overal average value of Median
frequency(Welch method) is %2.3f Hz\n',Avg_medianfreq1);


%%% Plot MDF graphics representatively only for Column = 5, Row = 13

    for column = 5
        for row = 13
            L = length(Data_cropped_1);
            t = (0:L-1)*T;

                  % MDF with Welch method calculation
                  n_t = numel(t);
                  seg_lth=500; % segment length
                  ovl_per=50; % 50 % of overlap
                  Hs = spectrum.welch('Hamming',seg_lth,ovl_per);

psd_welch=psd(Hs,matrDATA{row,column},'Fs',SamplingFrequency/2,'NFFT',n_t
,'SpectrumType','onesided'); % Hs : method (Welch)
                  normcumsumpsd =
cumsum(psd_welch.Data)./sum(psd_welch.Data);
                  Ind = find(normcumsumpsd <=0.5,1,'last');
                  medianfreq1{row, column} = psd_welch.Frequencies(Ind);

                  disp(['Column ', num2str(column),' : row ',
num2str(row)]);
                  fprintf('Median frequency Welch method is %2.3f
Hz\n',psd_welch.Frequencies(Ind));

                  figure();
                  plot(psd_welch);

        end
end
```

12.6 Author Publications

Publication I (Occupational Safety and Hygiene II. Taylor & Francis Group, London. 265-269)

High-Density Surface Electromyography Applications & Reliability vs. Muscle Fatigue – A Short Review

T. Sa-ngiamsak, J. Castela Torres Costa, J. Santos Baptista

Research Laboratory on Prevention of Occupational and Environmental Risks (PROA/LABIOMEP), University of Porto, Portugal

ABSTRACT

Muscle fatigue has been documented in various occupations. The aim of this study was to evaluate the applications of high density surface electromyography (HD-sEMG), in context of its variables/factors correlating with muscle fatigue, beside with its feasibility and reliability in muscle fatigue assessment. The search was performed over 33 electronic databases through integrated and metasearch search methods. Seven studies were included in the review. Four of them associated with HD-sEMG applications in muscle fatigue assessment and three other studies involving with reliability in muscle fatigue assessment. Evaluation by HD-sEMG is feasible and reliable in muscle fatigue assessment. There are many variables/factors correlated with muscle fatigue. Its reliability in terms of repetition and reproducibility of a diagnosis were also proved. This review indicates that applications of HD-sEMG are feasible and reliable in order to assess muscle fatigue whether static or dynamic contraction.

Publication II (Occupational Safety and Hygiene III. Taylor & Francis Group, London. 143-148)

The Applications of muscle fatigue/Muscle activity assessment using Multi-channel surface EMG during repetitive movement – A Short review

T. Sa-ngiamsak, J. Castela Torres Costa, J. Santos Baptista

Research Laboratory on Prevention of Occupational and Environmental Risks (PROA/LABIOMEP), University of Porto, Portugal

ABSTRACT

Repetitive movement is commonly observed in daily-life activities. Exposure to it for a long period of time can cause muscle fatigue. The aim of this study was to examine and present the applications of muscle fatigue/muscle activity assessment during the repetitive movement by using multi-channel surface EMG. The systematic searches were conducted over 35 electronic databases, through the search methods type of integrated and metasearch. Four studies were included in the review. Two of them were associated with one-dimensional array surface EMG, and another two studies were involved with two-dimensional array surface EMG. Both types and their utilization of advanced mathematic algorithm were capable to evaluate EMG signal during dynamic tasks. In order to have the higher accuracy and reliable results, the two-dimensional array surface EMG is required, due to its multiple detection sites can provide greater information detected over larger muscle fiber area.

Publication III (Accepted to be published from DYNA Journal 2016)

Multi-channel Surface EMG for Muscle fatigue/activation evaluation in Ergonomics: A Systematic Review

T. Sa-ngiamsak [a,d], C. Vila-Cha [b,c], J. Santos Baptista [a], J. Castela Torres Costa [a]

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[b] *Polytechnic Institute of Guarda, Portugal,*
[c] *Research Center in Sport Sciences, Health and Human Development (CIDESD), Portugal*
[d] *Department of Industrial Hygiene and Safety, Faculty of Public Health, Burapha University, Thailand*

ABSTRACT

Work-related muscle fatigue is one of the most prevalent health problems among workers. So far, the methods to precisely evaluate muscle fatigue/muscle activation are still limited, in terms of ergonomic applications. This study was carried out to examine and present the applications of muscle fatigue/muscle activation assessment during whether sustained or repetitive muscle contraction, by using multi-channel surface EMG. The systematic searches were conducted over 34 electronic databases, through the research from E-journals databases. Nine studies were found relevantly involved in sustained muscle contraction, and other five studies related to repetitive muscle contraction. Various signals evaluation methods, even new techniques and relevant parameters were demonstrated. The results showed that, by applying the multi-channel surface EMG, particularly with an array of two-dimensional electrodes type, along with its newly advanced mathematic algorithm had paid a key role in terms of reducing the variability of calculations, resulted from a non-uniformity of muscle activation, and moreover it comes up with the property of spatial distribution of muscle activity monitoring, which the conventional bipolar surface EMG is not capable to cope with.

Publication IV (Being in publication process by the time of this printing)

High-density surface EMG investigation over muscle fatigue of Work-related MSDs and healthy workers in real-world working condition

T. Sa-ngiamsak [a,d], C. Vila-Cha [b,c], J. Santos Baptista [a], J. Castela Torres Costa [a]

[a] *LAETA – Associated Laboratory for Energy, Transports and Aeronautics, Faculty of Engineering, University of Porto, Porto, Portugal*

[b] *Polytechnic Institute of Guarda, Portugal,*
[c] *Research Center in Sport Sciences, Health and Human Development (CIDESD), Portugal*
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ABSTRACT

Prolonged repetitive working in real-world working condition is one of the most potential causes of work-related MSDs problem. The recent evolutionary developed High-density surface EMG has been most introduced in laboratory setting tasks with highly potential performance. This study's purposes were to bring its superior properties in to the practical application, by utilizing it in the real-world industrial sectors, assessing onto the real existing workers, whether healthy or different cases of MSDs subjects history. High-density surface EMG 13 × 5 grid electrodes was applied over right upper trapezius muscle of five workers with shoulder MSDs, two workers with elbow & wrist MSDs, and thirteen healthy workers. All subject cases demonstrated different EMG manifestations in different conditions, basically increasing values or greater inclining slope of RMS, as well as decreasing values or greater declining slope of MDF, for further sign of fatigue. However these were also observed different for either MSDs case, depending on different existing muscle problem locations, which may have been connected to the workers adoption of alteration of muscle control and alternative movement strategy, having most likely transferred muscle load toward some synergistic muscles, due to fatigue and pain as a result of muscle fiber abnormality. Moreover the difference of EMG manifestations among sequential time over the workday, and across the workweek also observed. In addition subjective parameter, as local perceived fatigue over neck and shoulder also revealed some psychological aspects, linking to those of different conditions, whether over time issue or medical diagnosis issue. In conclusion, these all significant outcomes, may have proved the efficiency of its functions, in the real-world working conditions, and paved the ways for more advanced application to come.